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SIMULATION ASSESSMENT VALIDATION ENVIRONMENT (SAVE)

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FOREWORD

Commercial industry is leading the way in implementing the use of modeling and simulation tools to reduce product cost, time to market, etc. The use of these tools results in leaner systems that are more competitive in the global market. The emphasis within commercial industry is not only to stay in business, but become more profit conscious. Many companies are seeing declining revenues and higher profits. How is this possible? They have found ways to reduce cost, in other words make their products more affordable. This occurs in many ways from streamlined production, to the rapid introduction of new products, to strategic partnering, including outsourcing or co-sourcing.

The ability to simulate manufacturing operations, prior to actual production, is having a significant impact on product and process design decision making. Commercial simulation tools have matured rapidly in recent years, but their use is still somewhat limited by the lack of integration among sets of tools to evaluate cost, schedule, and risk. The SAVE program was initiated to address this required integration.

The concept of affordability is a central theme in the Joint Strike Fighter (JSF) program. This is seen in the genesis of the program that combines three distinct aircraft derivatives into one to leverage affordability by streamlining development and production cost. In concept, all three derivative aircraft are designed and manufactured jointly, with the exception of parts that are affected by customer specific requirements (e.g., Navy, carrier based models, require additional structural enhancements for the undercarriage). The design and manufacturing effort is characterized by a single design and manufacturing effort that encompasses all common parts with a split near the end to handle customer specific requirements. The net result will be an affordable fighter realized through the leveraging of common design and manufacturing efforts.

This concept is further expanded within the Manufacturing and Producibility Integrated Product and Process Team (IPPT) through the sponsorship of six key technology maturation initiatives including:

- JSF Manufacturing Capabilities Tool Set (JMCATS) – Developing a tool set for analyzing manufacturing risk and capabilities with traceability back to basic product requirements and functions.

- JSF Manufacturing Demonstration Program (JMD) – Developing an IPPT process with supporting tools to assess manufacturing cost directly from CAD data bases and to collect manufacturing information needed to drive cost engines.

- Virtual Manufacturing Fast Track Program – An initial JSF demonstration to show the usefulness of virtual manufacturing using an integrated environment of available software design and manufacturing tools.

- Ribbonized, Organized, Integrated (ROI) Wiring Program – A JSF demonstration to show the potential weight and cost savings using an ROI wiring architecture in a tactical aircraft.

- Manufacturing Affordability Development Program (MADP) – A JSF Government Team survey of twelve companies at seventeen facilities to identify pockets of manufacturing and producibility successes which demonstrated affordability potential for the remainder of the industry.

- Simulation Assessment Validation Environment Program (SAVE) – Develop a virtual manufacturing environment through the integration of a set of simulation, modeling and analysis tools.

Combined these programs are estimated to enable a 12%-20% reduction in life cycle cost through demonstration and implementation of improved processes and tools which reflect manufacturing considerations early in design.

These programs were identified as a result of the 1994 Government Led Lean Forum Workshop. The consensus topics from this workshop were Integrated Design and Cost; Modeling and Simulation; Teaming; Factory Operations; and Design for Quality and Producibility. The results of this workshop have led to the JSF sponsored tech-mat programs listed above. The SAVE program addresses the consensus topic of Modeling and Simulation.

The SAVE program is the integration of best of breed commercial off the shelf tools that support the generation and analysis of data needed to make earlier affordability based decisions. This leads to an ability to perform cost/performance trade studies, thereby enabling the treatment of cost as an independent variable by making cost clearly quantified as design requirements and decisions are made. The integration is leveraging work from other DoD organizations so that results are attainable much faster than possible without these capabilities. The end result will be a new set of commercially available capabilities that can support the entire JSF customer, prime, team, supplier and user base. SAVE provides the ammunition to drive affordability at all levels in the program. The SAVE program is estimated to contribute to 1%-2% of the life cycle cost reductions listed above.

This report documents the efforts under the SAVE Program to develop, demonstrate, validate, and plan for commercialization of a software environment in which users can easily integrate commercial or "home-grown" manufacturing simulation tools. The SAVE Program included two development phases, three formal demonstrations, and beta testing at two sites, and was supported by two advisory boards; an Operational Task Force, and a Technical and Business Advisory Board.

PREFACE AND ACKNOWLEDGMENTS

This report provides a summary of all activities during the entire life of the program and has been prepared for USAF/AFMC/ASC AFRL/MLMS as CDRL number A001 for contract number F33615-95-C-5538.

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Bob Bassett	Architecture/Infrastructure IPPT Lead
Marcia Herndon	Tool Integration IPPT Lead
Paul Collins	Demonstration/Technology Transfer IPPT Lead
Kathy Jacobson	Enhanced Design Cost Integration IPPT Lead

LIST OF ACRONYMS AND ABBREVIATIONS

ABC	-	Activity Based Costing
ADAM	-	Affordable Design And Manufacturing
AFMC	-	Air Force Materiel Command
AFRL	-	Air Force Research Laboratory
AIC	-	Artificial Intelligence Center
AIMS	-	Agile Infrastructure for Manufacturing Systems
ANSI	-	American National Standards Institute
API	-	Application Programming Interface
ASC	-	Aeronautical Systems Center
Assy	-	Assembly
ASURE	-	Analysis System for Uncertainty and Risk Estimation
BAFO	-	Best and Final Offer
BCL	-	Batch Control Language
BOM	-	Bill of Material
CA	-	Cost Advantage
CAD	-	Computer Aided Design
CATIA	-	Computer Aided Three Dimensional Interactive Application
CAx	-	Computer Aided (Anything)
CDA	-	Concept Demonstrator Airplane
CDE	-	Common Desktop Environment
CDF	-	Common Data File
CDP	-	Concept Demonstrator Program
CDRL	-	Contract Data Requirements List
CE	-	Concurrent Engineering
CER	-	Cost Estimating Relationship
COM	-	Common Object Model
CORBA	-	Common Object Request Broker Architecture
COSE	-	Common Open System Environment
COTS	-	Commercial Off the Shelf
CSA	-	Close Support Aircraft
CSC	-	Computer Science Corporation
CTC	-	Concurrent Technologies Corporation
DARPA	-	Defense Advanced Research Project Agency
DB	-	Database
DDI	-	Decision Dynamics Incorporated
DEAM	-	Design Engineering Analysis Model
DFM	-	Design for Manufacturability
DICE	-	DARPA Initiative on Concurrent Engineering
DID	-	Data Item Description
DLL	-	Dynamic Link Library
DMC	-	Defense Manufacturing Conference
DNS	-	Domain Name Service

DoD	-	Department of Defense
DOE	-	Design of Experiments
E&MD	-	Engineering and Manufacturing Development
EAF	-	Estimate Adjustment Factor
EAI	-	Engineering Animation, Incorporated
EBOM	-	Engineering Bill of Materials
ECRC	-	Electronic Commerce Resource Center
EDN	-	Electronic Design Notebook
EMD	-	Engineering & Manufacturing Development
ERGO	-	Ergonomics Option
ERP	-	Enterprise Resource Planning
FA	-	Factor AIM
Fab	-	Fabrication
GD&T	-	Geometric Dimensioning & Tolerancing
GDT	-	Geometric Dimensional Tolerancing
GE	-	General Electric
GIFF	-	Graphical Interface File Format
GII	-	Graphic Interactive Interface
GIT	-	Georgia Tech Institute of Technology
GRCI	-	General Research Corporation International
GSL	-	Graphics Simulation Language
GUI	-	Graphical User Interface
H/W	-	Hardware
HTML	-	Hypertext Markup Language
I/F	-	Interface
I/O	-	Input/Output
IBAM	-	Industrial Base Analysis Model
IBM	-	International Business Machines
ID	-	Identification
IDL	-	Interface Definition Language
IGES	-	Initial Graphics Exchange Specification
IGRIP	-	Interactive Graphics Robot Instruction Program
IIOP	-	Internet Inter-ORB Protocol
IP	-	Internet Protocol
IP/PD	-	Integrated Product/Process Development
IP/PT	-	Integrated Product/Process Team
IPAM	-	Industrial Production Analysis Model
IPD	-	Integrated Product Development
IPPDB	-	Integrated Product Process Database
IPPT	-	Integrated Product and Process Team
IPT	-	Integrated Product Team
IRS	-	Interface Requirements Specification
ISO	-	International Standards Organization
JAR	-	JAVA Application Resource
JAST	-	Joint Advanced Strike Technology
JDK	-	JAVA Development Kit

JMCATS	-	JSF Manufacturing Capabilities Assessment Tool Set
JMD	-	JSF Manufacturing Demonstration
JPO	-	Joint Program Office
JSF	-	Joint Strike Fighter
KB	-	Knowledge Base
KC	-	Knowledge Center
LAI	-	Lean Aerospace Initiative
LCAM	-	Life Cycle Analysis Model
LCC	-	Life Cycle Cost
LHS	-	Left Hand Side
LM	-	Lockheed Martin
LMMS	-	Lockheed Martin Missiles and Space
LMSW	-	Lockheed Martin Skunk Works
LRIP	-	Low Rate Initial Production
MADE	-	Manufacturing Automation and Design Engineering
MADP	-	Manufacturing Affordability Development Program
MBOM	-	Manufacturing Bill of Materials
MDF	-	Metadata File
ME	-	Manufacturing Engineer
MECE	-	Multimedia Environment for Concurrent Engineering
Mfg	-	Manufacturing
Mgt	-	Management
MRP	-	Manufacturing Resource Planning
MS	-	Microsoft
N/C	-	Numerical Control
NB	-	Net Builder
NC	-	Numerical Control
NFS	-	Network File System
NIIIP	-	National Industrial Information Infrastructure Protocol
NIST	-	National Institute of Standards and Technology
ODBC	-	Open Data Base Connectivity
OMG	-	Object Management Group
OO	-	Object Oriented
ORB	-	Object Request Broker
OSHA	-	Operational Safety and Health Administration
OTF	-	Operational Task Force
P&W	-	Pratt and Whitney
PC	-	Personal Computer
PCA	-	Physical Configuration Audit
PCM	-	Production Cost Model
PDM	-	Product Data Manager
PDR	-	Preliminary Design Review

PEO	-	Program Engineering Office
PIE	-	Probabilistic Inference Engine
POOP	-	Plain Old Orbix Protocol
QM	-	Query Manager
QUEST	-	Queuing Event Simulation Tool
R&D	-	Research & Development
RADM	-	Rear Admiral
RASSP	-	Rapid Prototyping of Application Specific Signal Processors
RDB	-	Relational Database
RDE	-	RASSP Design Environment
RFP	-	Request for Proposal
RHS	-	Right Hand Side
ROI	-	Return on Investment
ROI	-	Ribbonized, Organized, Integrated Wiring
RPC	-	Remote Procedure Call
S/W	-	Software
SAIC	-	Science Applications International Corporation
SAVE	-	Simulation Assessment Validation Environment
SBD	-	Simulation Based Design
SCRA	-	South Carolina Research Authority
SDAI	-	Software Data Access Interface
SDE	-	SAVE Design Environment
SDM	-	SAVE Data Model
SDR	-	System Design Review
SGI	-	Silicon Graphics Incorporated
SLMC	-	Sanders a Lockheed Martin Company
SMC	-	Systems Modeling Corporation
SQL	-	Structured Query Language
SRR	-	Scrap, Rework, and Repair
SS	-	Source Selection
STAM	-	Strategic Technologies Analysis Model
STL	-	SteroLithography
T/BAB	-	Technical/Business Advisory Board
TBD	-	To Be Determined
TCP/IP	-	Transmission Control Protocol/Internet Protocol
TDM	-	Technical Data Management
UG	-	UniGraphics
USAF	-	United States Air Force
USC	-	University of Southern California
VM	-	Virtual Manufacturing
VP	-	Virtual Prototyping
VSA	-	Variability Simulation Analysis
WFM	-	Work Flow Manager
WL	-	Wright Laboratory
WPAFB	-	Wright Patterson Air Force Base

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ABSTRACT

The Joint Strike Fighter (JSF) Simulation Assessment Validation Environment (SAVE) Program provides the capability to assess the manufacturing impacts of both product and manufacturing process design decisions. By integrating Commercial Off-The-Shelf (COTS) modeling and simulation tools into a *seamless virtual environment*, SAVE allows design teams to develop and verify new affordable aircraft concepts before developing expensive hardware.

The SAVE infrastructure utilizes a Common Object Request Broker Architecture (CORBA) based shared Data Model and Work Flow Manager and a commercial *Electronic Collaborative Design Notebook* to integrate a suite of six commercial manufacturing tools which include schedule, factory, assembly, dimensional variability, cost, and risk simulations. In the future, other tools may be added by developing simple SAVE-compliant CORBA wrappers, and SAVE will be available to extend to other problem domains such as operations and support simulations to assess life-cycle issues.

SAVE expects to achieve significant cost savings for the JSF Program by providing integrated design teams the capability to quickly perform "what-if" studies and accurately define a product's cost and risk early in the design process. For the JSF, a potential 1%-2% cost avoidance is projected. While the SAVE initiative is vital to achieve the affordability goals of the Joint Strike Fighter, the implementation of SAVE in other design and manufacturing environments has the potential to generate equally impressive cost savings.

This report presents a programmatic overview of SAVE and describes the activities of development, demonstration, validation, and planning for implementation and commercialization. This report covers the full period of the SAVE Program, from April 1995 through September 2000. A detailed description of the SAVE software system is documented in the SAVE Software Product End Item Report and information for users of the system is presented in the SAVE Software User's Manual.

Chapter 1

Program Overview

SAVE Final Report

Contract Number F33615-95-C-5538

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1.0 Summary

The 1994 Lean Aircraft Initiative industry forum, identified the application of Virtual Manufacturing (VM), in the form of integrated simulation technologies, as a key enabler in reducing cost and increasing quality. The Joint Strike Fighter Program initiated the Simulation Assessment Validation Environment (SAVE) Program to integrate a set of VM tools and to validate the potential savings through a series of demonstrations. This report describes the SAVE program and its potential for a 1%-2% lifecycle cost avoidance on the Joint Strike Fighter program.

2.0 Introduction

Virtual Manufacturing is the integrated use of design and production models and simulations to support accurate cost, schedule, and risk analysis. These modeling and simulation capabilities allow decision-makers to rapidly and accurately determine production impact of product/process alternatives through integrating actual design and production functions with next generation simulation. The use of simulation software to achieve the objectives of virtual manufacturing has been rapidly increasing throughout industry. The potential for these tools to significantly improve affordability and reduce cycle times is widely accepted, but the potential has not been fully achieved.

Many commercial manufacturing simulation tools with excellent capabilities exist on the market today. Although, many of these tools rely on similar types of data, differences in internal storage structures and nomenclature have prevented easy tool to tool data integration. Often, large amounts of data must be reentered, at considerable time and expense, to accommodate these differing formats. Some point-to-point solutions do exist between specific tools, but as the number of tools grows, this integration solution becomes unmanageable, and the benefits from using an integrated tool suite go unrealized.

The Simulation Assessment Validation Environment (SAVE) program, conducted by Lockheed Martin and funded by the Joint Strike Fighter Program Office, addressed these limitations by developing and implementing an open architecture environment to integrate modeling and simulation tools. SAVE also demonstrated that this integrated simulation capability can significantly reduce weapon system life cycle costs (LCC).

The initial phase of the program, completed in August 1996, established a core tool suite integrated via the Defense Advanced Research Projects Agency (DARPA) developed Rapid Prototyping of Application Specific Signal Processors (RASSP) architecture. The core tool suite incorporated commercial CAD, factory simulation, assembly simulation, schedule simulation, cost and risk modeling capabilities.

During the interim cycle of Phase II, the SAVE team developed a Common Object Request Broker (CORBA) based approach to tool integration which provides a solid foundation for the ultimate production use and commercialization of SAVE. The CORBA-based infrastructure includes the SAVE Common Data Model, a Workflow Manager, and a Query Manager for interactive access to the Data Model, and an expanded tool suite. A commercial Electronic Collaborative Design Notebook, considered essential to SAVE, was used but not developed under the contract. SAVE demonstrations have used tools from Nexprise, Inc. and Netscape's Collabra.

The final cycle of Phase II, including the Final Demonstration, further expanded the Data Model, investigated access to multiple back-end data stores, and matured the various tool wrappers. The final contract version of SAVE was validated during the Final Demonstration in September 1999.

3.0 Objectives of SAVE

In recent years, manufacturing modeling and simulation software has experienced increased use throughout industry. Rapid advances in computing hardware and software now allow accurate simulations of complex processes. Computer graphics provide Integrated Product/Process Teams (IPPT) with the means to efficiently understand the results of these simulations and make critical design and manufacturing decisions, without resorting to costly physical prototypes.

Growth in the use of virtual manufacturing tools has been limited by the costly, manual transfer of data among the set of simulation tools. Typically, a design team will use a 2-D or 3-D CAD package for design. The team will then assess the manufacturing impact of product and process decisions through use of a set of virtual manufacturing tools to assess cost, schedule, and risk. The tool capabilities typically include:

- Process planning
- Dimension and tolerance analysis
- Schedule simulation
- Assembly simulation
- Factory simulation
- Ergonomic simulation
- Feature-based costing

These tools use much of the same data as input, but each requires a different internal data format. Manual reformatting and reentry of these data are prohibitively costly.

In 1994, a U.S. Government led Lean Forum Workshop reached consensus on a set of critical investment areas focused on overall weapon system affordability. These areas included:

- Integrated design and cost
- Modeling and simulation
- Teaming
- Factory Operations
- Design for quality and producibility

Based on this Government/Industry consensus, the Joint Strike Fighter program office initiated the SAVE program. The objective of SAVE is to demonstrate, validate and implement integrated modeling and simulation tools and methods used to assess the impacts on manufacturing of product/process decisions early in the development process. The key anticipated results of the SAVE program are the demonstration of an initial Virtual

Manufacturing capability, and the validation of this capability to reduce the maturation costs and risks associated with the transition of advanced product and process technologies into production.

Understanding the development process metrics impacted by SAVE is central to managing SAVE development to achieve the maximum improvements in these metrics. The following product/process metrics were selected to guide SAVE development:

- *Design to cost data accuracy* – accurate cost prediction improves design decisions and requires less iteration to achieve desired cost
- *Lead time reduction* – provides for process optimization leading to better schedules and closer to just-in-time factory
- *Design change reduction* – improved, affordable designs with fewer errors reduces need for late design changes
- *Scrap, rework, repair reduction* – many product/process problems identified prior to design release, not on shop floor
- *Process capability* – processes that control key characteristics of critical parts and assemblies can be analyzed for their cost impacts
- *Inventory turn time reduction* – factory processes and layout are optimized through simulation to provide better just-in-time performance
- *Fabrication & assembly inspection reduction* – designed-in quality verified through simulation reduces need for separate inspection operations

Early in the SAVE program the proposed capability and approach of the SAVE solution were described to members of the Integrated Product/Process Teams working on the F-22 Advanced Tactical Fighter. These active design teams estimated the significant potential benefits, shown in Table 1-1, for the proposed SAVE integrated virtual manufacturing system. Adjustments were made for the Joint Strike Fighter Program based on differences in acquisition programs and design phases.

Table 1-1. SAVE Affordability Metrics

PRODUCT/PROCESS METRIC	Potential SAVE Impact To Metric (%)	
	F-22	JSF
Design to Cost Data Accuracy	25	12
Lead Time Reduction	5	10
Design Change Reduction	15	28
Scrap, Rework & Repair Reduction	15	11
Process Capability	10	5
Inventory Turn Reduction	5	2
Fab & Assy Inspection Reduction	13	6

As a result of the SAVE Program's enhanced virtual design and manufacturing environment, and tools, the program's benefits forecast a potential cost avoidance of 1 percent to the F-22 current air vehicle average unit cost. For a new acquisition system like JSF, the potential benefits are projected to be approximately 1%-2% of the total Life Cycle Cost – a potential cost avoidance of $1 Billion.

4.0 SAVE Program Plan

SAVE is being developed in two phases. Major elements of the program plan are illustrated in Figure 1-1. During Phase I, completed in December 1996, the SAVE team developed the overall Concept of Operations for the SAVE tool set. This initial concept of how to apply virtual manufacturing simulation tools provided the core requirements for both the infrastructure and tool integration approaches and provided the basis for the initial demonstration, which is discussed in Section 5.4.

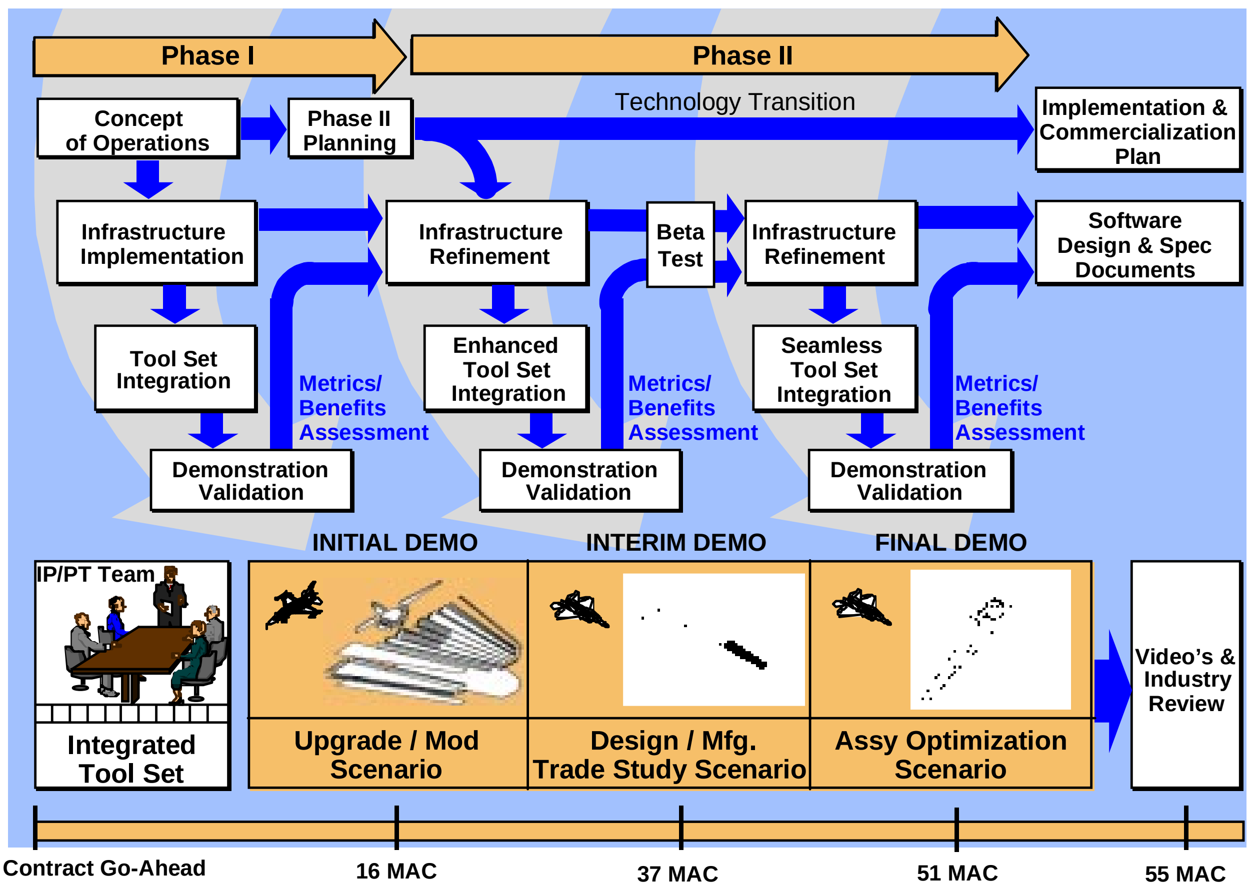


Figure 1-1. SAVE Program Plan

During Phase II the SAVE system was refined for both implementation and validation, leading to a system ready for initial production use and commercialization. Phase II contains two cycles, each of which build on the efforts of the previous phase and lead to a more comprehensive demonstration. Both the Interim and Final demonstrations involved application of SAVE to on-going F-22 design activities. Formal beta testing at the two JSF prime contractor sites was conducted during Phase II with completion in mid-1999.

During each cycle, the concept of operations was updated based on the latest experience with the SAVE environment. The published Concept of Operations, available in the SAVE Software User's Manual, provides an excellent starting point for organizations beginning SAVE implementation. This document may be obtained through the JSF program office, or by contacting the Air Force Program Manager at WPAFB/MLMS. While the documented operational concepts provide a successful approach to the use of virtual manufacturing tools, the SAVE system does not rigidly implement one approach. Rather, SAVE allows IPPTs to flexibly determine the process to be used for each design study. IPPTs will map their desired process into the work flow manager, which will support but not constrain the team.

SAVE infrastructure and tool integration concepts were refined in Phase II. During the Interim cycle, SAVE was significantly redesigned to reflect the eventual production approach, although its implementation was somewhat limited for the demonstration and beta test. In the Final cycle, SAVE was extended and enhanced based on both Interim demonstration and beta test experiences.

Major deliverables from SAVE included videos of each major demonstration, the software specification and design documents, and an Implementation and Commercialization Plan, briefly described in Section 5.5.

The SAVE program plan provided for formal beta testing of the SAVE system by the two JSF prime contractors. Desire for beta testing was voiced by representatives of the SAVE advisory groups, which represent potential users and commercial software vendors. Both groups believe that this testing was necessary to more rapidly mature the SAVE software and to address the difficult cultural issues of real production implementations.

Both JSF Prime contractors, Lockheed Martin Tactical Aircraft Systems and Boeing Military Aircraft, were selected to participate in determining SAVE functionality needed for testing. Beta tests were scoped to run for approximately 7 months and included the broad Interim demonstration capability and more complete functionality with a limited set of simulation codes.

SAVE was designed as an open system and its design specifications were made widely available during the contract as well as in final delivered form. This was done to maximize the review and feedback from prospective users, commercial software vendors, and standards development activities.

5.0 Technical Approach to SAVE

The SAVE program encompasses five distinct elements:

- Tool execution infrastructure
- Simulation tool integration
- Feature-based cost models
- Demonstrations
- Implementation/Commercialization planning

Each of these is briefly described here and is more fully discussed in later sections.

5.1 Infrastructure

The SAVE program approach to overall infrastructure and tool integration is shown in Figure 1-2. Major elements of this architecture include the classes of manufacturing simulation codes, Common Object Request Broker Architecture (CORBA) compliant code "wrappers", the SAVE Data Server, a Work Flow Manager, a web-based data browser referred to as the Query Manager, an Electronic Design Notebook, and back-end data storage systems (tailored to each implementation).

The SAVE architecture provides a set of infrastructure tools to aid Integrated Product/Process Teams with the operation of the SAVE integrated tools in an organized manner. This infrastructure includes all of the system elements excluding the commercial simulation tools. SAVE will implement a flexible open architecture allowing new tools to be easily plugged into the overall system. These tools are supported by the following infrastructure elements:

- Automated work flow management
- Manual code launch
- Distributed electronic design notebook
- Data model browser for access and reuse

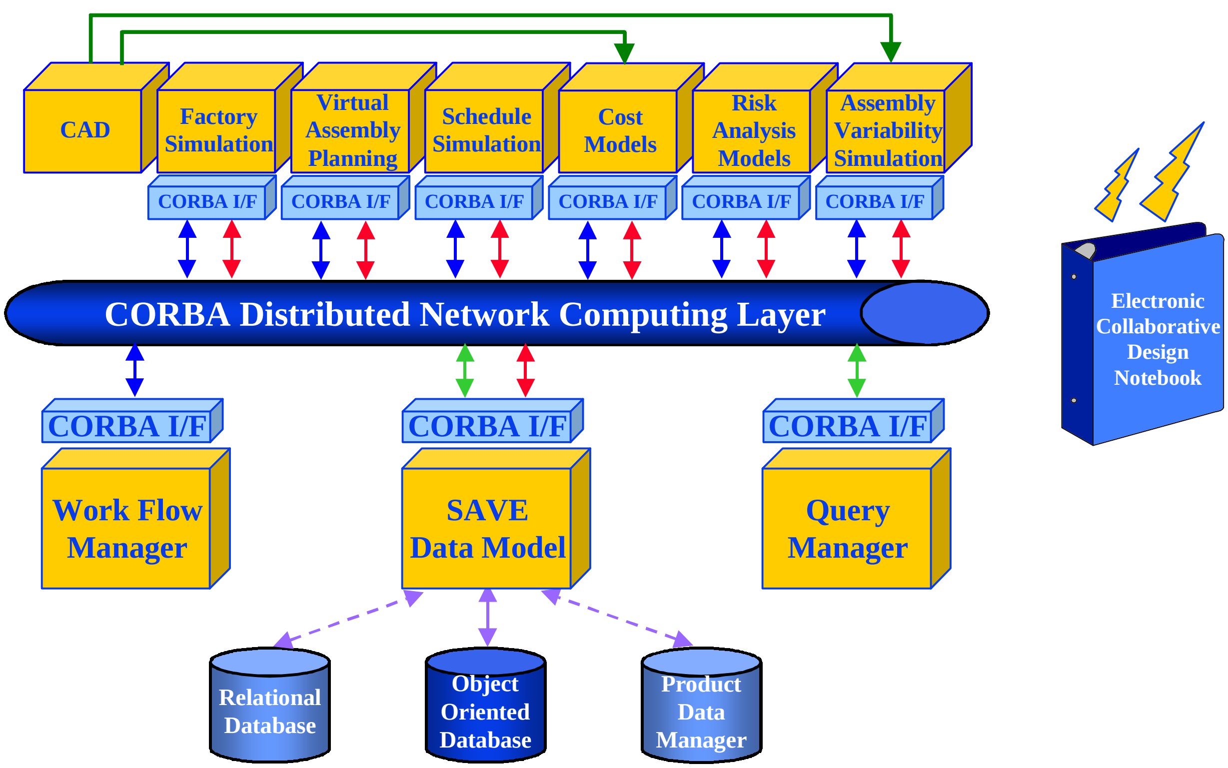


Figure 1-2. SAVE Architecture and Approach

The SAVE infrastructure also contains low level elements supporting communications and data repository management.

Elements of the SAVE infrastructure are implemented as distributed CORBA objects to provide a flexible, expandable system which operates in a distributed heterogeneous computing environment. Integrating a new virtual manufacturing code to operate within SAVE involves wrapping for workflow manager (WFM) support and wrapping for data integration. Approximately 80 person hours are required to interface with the WFM. Effort to interface with the object-oriented data model varies with the amount of input/output required but is estimated to require 200-300 person hours.

5.2 Tool Integration

The simulation tool classes shown in Figure 1-2 are used to assess the cost, schedule, and risk of product and process design decisions. The SAVE system supports a range of manufacturing simulation classes but is not dependent on the particular commercial tools chosen for use on the contracted effort. While the SAVE team considers the particular tools selected for the contract, shown in Table 1-2, to be best in class, other tools can be substituted and new classes of simulation codes (within the manufacturing simulation domain) can be added by simply wrapping the code with a SAVE compliant interface to the WFM and data model server. SAVE Architecture and Tool Integration Specification documents have been released into the public domain and are available by request from the JSF program office or from The Air Force Research Laboratory.

Table 1-2. SAVE's Demonstration Tool Set

TOOL CATEGORY	VENDOR	TOOL NAME
CAD	IBM/Dassault	CATIA
Cost Modeling	Cognition Corporation	CostAdvantage
Schedule Simulation	Symix	FACTOR/AIM
Assembly Simulation	Deneb Robotics	IGRIP/ERGO
Factory Simulation	Deneb Robotics	QUEST
Risk Assessment	SAIC	ASURE
Assembly Variability Simulation	EAI	VSA 3D

The CORBA standard for distributed interoperable object computing was selected to simplify running a SAVE system on a distributed, heterogeneous computing network. An object-based SAVE Data Server, built using CORBA, effectively isolates the individual simulation codes from having to deal with the actual data storage systems, which will likely be different for each SAVE implementation. For the SAVE Phase 2 Demonstrations and Beta Testing, data objects were stored in a single object-oriented database. The SAVE Data Model Server allows data to be stored in multiple back-end stores (relational databases, PDMs, etc.), as required by an implementation site, to eliminate problems of data redundancy and management.

5.3 Feature Based Cost Models

The SAVE Cost Modeling System, built on the Cognition Corporation's Cost Advantage product, is comprised of a series of knowledge bases that are used to define cost and producibility rules for manufacturing processes based on information about product features. SAVE developed four cost models, which were validated in demonstrations and delivered to Cognition for commercialization. Site specific data are stored in external tables allowing easy implementation and customization.

These cost models include:

- 5-Axis machined parts
- Hand lay-up composite parts
- Sheet metal
- Assembly cost model

Each of these models rely on the CAD feature extraction capabilities provided by the CAD CostLink. This link interprets features that are modeled in the CAD system, extracts their definition, and makes the information available to the cost model. Typical inputs and outputs associated with the four SAVE cost models are shown in Table 1-3.

Table 1-3. Typical Cost Model Data

COST INPUTS	COST OUTPUTS
Feature Parameters	Recurring Mfg Labor Cost
Material Selection	Recurring Material Cost
Process Selection	Non-recurring Tool Mfg Cost
Number or Units	Non-recurring Tool Mtrl Cost
Units per Aircraft	Non-recurring Engineering Cost
Weight	First Unit Cost
Programmatics	Sustaining Tool Eng Cost
Other	Sustaining Tool Mfg Cost
	Quality Assurance Cost
	Process Plan Simulation

5.4 SAVE Demonstrations

The SAVE program includes three major demonstrations, illustrated in Figure 1-3 and discussed below.

The objective of the Phase I demonstration was to validate that a set of disparate commercial off-the-shelf simulation tools could be seamlessly integrated and that this integrated set of tools would produce results that closely correlate to manufacturing actuals from a real world production program. The component selected for this validation was the F-16 horizontal stabilizer. This component was selected for three reasons:

(1) The stabilizer structure was dramatically changed during the redesign;

(2) The change made to the stabilizer was isolated from most other manufacturing activities so that the data collected from historic files could be easily isolated for direct correlation to the simulated data; and

(3) The F-16 program provides an extensive database that could be used to analyze the simulation results.

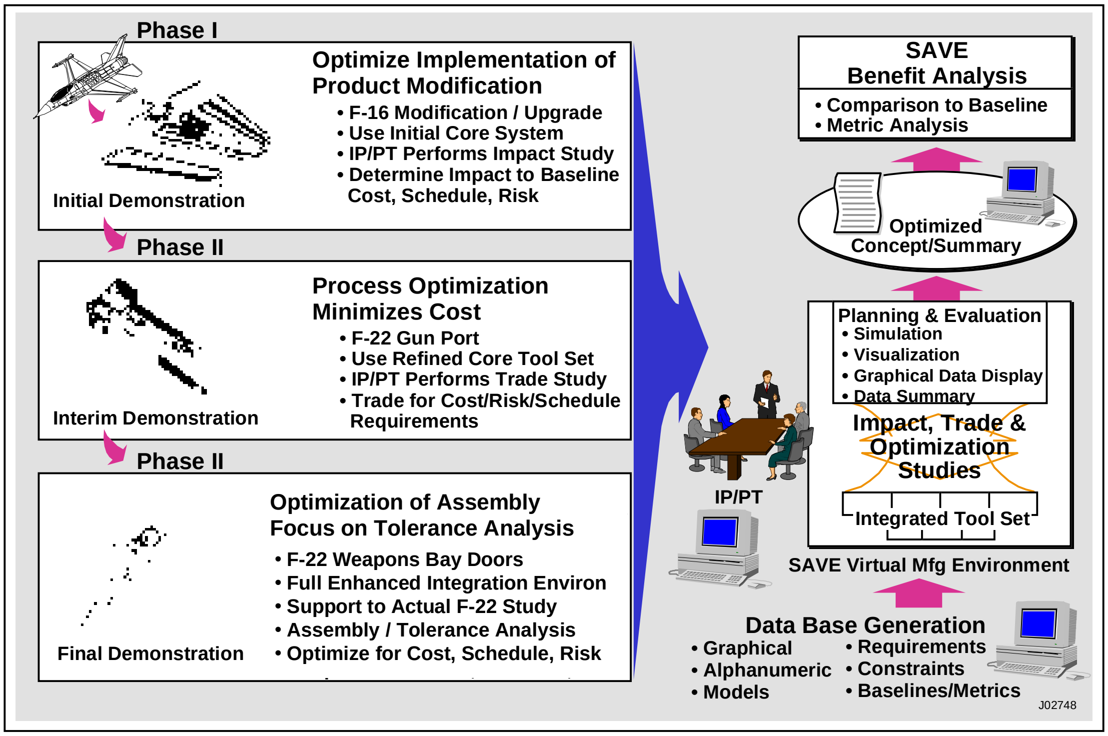


Figure 1-3. SAVE Demonstrations Validate the System

SAVE simulation estimates of cost, schedule, and risk correlated well with actuals; cost was within 15%, schedule was within 18%, and risk was within 3% of F-16 program data. SAVE was successfully used on the Initial demonstration and measurable progress was made on each of the program metrics. Details of this demonstration are documented in Chapter 4.

The Phase II Interim Demonstration applied SAVE to a typical design/manufacturing trade study scenario, the redesign of the F-22 gun port. Design changes were required for performance reasons, but affordability was a key design driver. A major criterion that supported the selection of the gun port redesign was applying SAVE to an on-going design activity thus increasing the reality of the demonstration, providing eventual actual data for the metrics, and beginning SAVE implementation on the F-22 program. Chapter 5 provides a discussion of this demonstration.

In the Final Demonstration, SAVE was applied to a major assembly optimization scenario, focusing on the F-22 weapons bay doors and their complex tolerance issues. This demonstration applied the final contract version of the SAVE system and is documented in Chapter 6.

5.5 Implementation/Commercialization Planning

The SAVE program is not intended to produce a complete production implementation of the capability described here. The SAVE team has:

- Produced a viable approach to an integrated virtual manufacturing system.
- Validated that approach through realistic demonstrations.

- Validated the basic premise that virtual manufacturing simulations will achieve significant affordability benefits.

- Developed plans to make a SAVE system commercially available in time to support the JSF Engineering & Manufacturing Development program.

- Developed implementation plans to aid prospective users in rapidly bringing SAVE to productive use.

Progress toward commercialization is very encouraging, based on wide acceptance of SAVE's approach to integration and the success of the three demonstrations. All SAVE simulation code vendors can provide commercial SAVE-compliant versions of their codes. One of the current vendors (Cognition) has developed a commercial SAVE Data Model server, based on their Knowledge Center object management system.

A comprehensive implementation planning approach was developed including a detailed notional schedule for all tasks. A spreadsheet is available that helps potential implementers estimate the implementation costs and benefits for use of a SAVE system. More complete summary information is included in Chapter 7 of this document and full details of SAVE implementation planning are discussed in the SAVE Software User's Manual.

Chapter 2s

Architecture and Tool Integration

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 The Architecture and Tool Integration Team

The development of the SAVE architecture and tool integration approach was truly a team effort involving experts on computing infrastructure, data modeling, modeling and simulation, and vendor tools. Table 2-1 lists the contributing members of this team.

Table 2-1. Team Members

MEMBER	EXPERTISE
Lockheed Martin Aeronautical Systems	Computing Infrastructure, Architecture Concepts, Data Modeling, CORBA, C++ and JAVA Programming
Sanders, A Lockheed Martin Company	Computing Infrastructure, Architecture Concepts, RASSP Experience
Lockheed Martin Missiles and Space	JAVA Programming, CORBA, SBD Knowledge
Lockheed Martin Tactical Aircraft Systems	Modeling and Simulation, Vendor Tools
Cognition Corporation	Vendor Tools, Modeling and Simulation
Deneb Robotics	Vendor Tools, Modeling and Simulation
Engineering Animation	Vendor Tools, Modeling and Simulation
SAIC	Vendor Tools, Modeling and Simulation
Symix	Vendor Tools, Modeling and Simulation

2.0 Approach

The SAVE architecture provides the infrastructure to aid Integrated Product/Process Teams with the operation of the SAVE simulation tools in an integrated, distributed virtual manufacturing environment.

The architecture and tool integration concepts were developed and deployed incrementally throughout the program. This phased approach allowed the team to select and focus areas for each phase while building on the successes and lessons-learned from the previous phase(s). Phase I activities focused on demonstrating data sharing while defining the content of the shared data. Phase II was divided into two parts. The first evaluated approaches for data exchange and the second refined the implementation of that approach including specifics of the common data model. This chapter discusses the key findings and results of these activities.

During Phase I, the team developed the common data file (CDF) format for data sharing. This was a flat file representation of the data that could be shared among the simulation tools. The CDF did not include all of the data elements needed in a production system, but it provided a forum for testing tool integration and data sharing concepts.

With the start of Phase II of the SAVE Program, the Tool Integration IPT built upon the work conducted during Phase I, including the lessons learned, to define the approach for Phase II. The primary objectives for this phase were to

- determine the approach for tool integration,
- define the SAVE data model,
- further document tool input/output requirements,
- determine the necessary level of tool integration,
- work with tool vendors to implement SAVE interfaces, and
- implement the toolsuite at the demo and beta sites.

The SAVE tool integration team investigated several approaches to tool integration that provide a mechanism for data exchange among manufacturing simulation tools, independent of both data location and storage mechanism. One option included storing the shared data in a database (either relational or object oriented) and writing tool interfaces directly to the database. This approach proved undesirable because of its reliance on a specific database product. The product dependence would cause one of two situations: users would be forced to store their information in the specific database product chosen for SAVE or tool vendors would have to reprogram their interfaces for every database product desired by a user. The second option reaps the advantages of database storage without the burdens by adding an abstraction layer between the tool vendor applications and the database. The Object Management Group developed the Common Object Request Broker (CORBA) standard for abstracting this information, thus, making it independent of application and platform. This approach allows for maximum flexibility with users able to store information in the location and product of their choice and tool vendors able to develop a single client application that satisfies all user requirements.

The SAVE architecture contains several components that, when combined, provide a virtual manufacturing (VM) environment. This environment is achieved through the integration and data sharing among commercially available software and is shown in Figure 2-1.

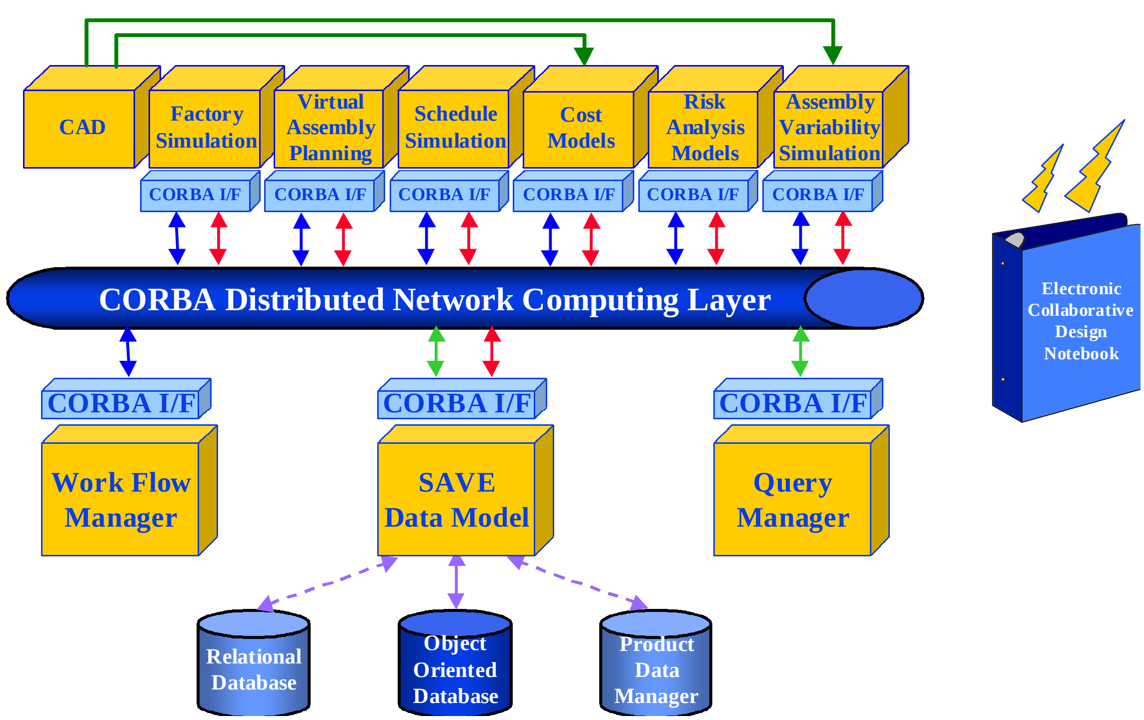


Figure 2-1. SAVE Architecture

3.0 Vendor Tools

One element of the architecture includes classes of manufacturing simulation tools. These tools represent the major categories of simulation and analysis that are needed in a virtual manufacturing environment. Table 2-2 shows the classes of tools being addressed along with the specific software that was implemented as part of the SAVE program.

Specific vendor tools considered best in class were integrated into the infrastructure as part of the formal program. However, the SAVE infrastructure is a flexible, open architecture that allows new tools to be easily integrated into the overall system. The current estimates for integrating a new commercial tool into the SAVE environment is approximately 300 person hours.

Table 2-2. SAVE Tools

TOOL CLASS	VENDOR	TOOLS
CAD	Dassault	CATIA
Factory Simulation	Deneb Robotics	QUEST
Virtual Assembly Planning	Deneb Robotics	IGRIP/ERGO
Schedule Simulation	Symix	Factor AIM
Cost Modeling	Cognition	Cost Advantage
Risk Analysis	SAIC	ASURE
Assembly Variability Simulation	EAI	VSA3D

3.1 CAD

The CAD tool provides the geometric definition of the product and is typically populated by a user. The information produced as a part of the CAD model is useful for any category of simulation tool that needs the product representation. Figure 2-1 shows two existing direct interfaces from the CAD tool to Cost Models and Assembly Variability Simulation. These interfaces exist for four major CAD tools and allow CAD to be loosely coupled to SAVE. In future versions of SAVE, the CAD tool could be wrapped to output cost and tolerance feature data directly into the SAVE Data Model. Figure 2-2 shows the top-level interfaces for a typical CAD tool.

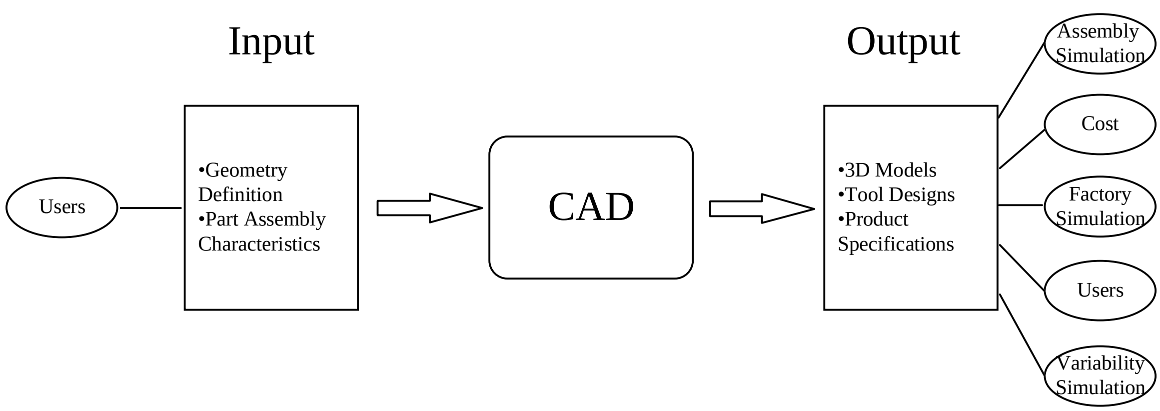


Figure 2-2. CAD Tool Interfaces

3.2 Factory Simulation

The factory simulation tool uses the process plan information as well as factory layouts to provide factory planning including throughput, layout, and resource allocation. Inputs are provided by a variety of sources, including the schedule simulation and assembly planning tools. The data provided by this class of tool is used in estimating cost, schedule, and risk for the design alternative being simulated. Figure 2-3 shows the top-level interfaces for a typical factory simulation tool.

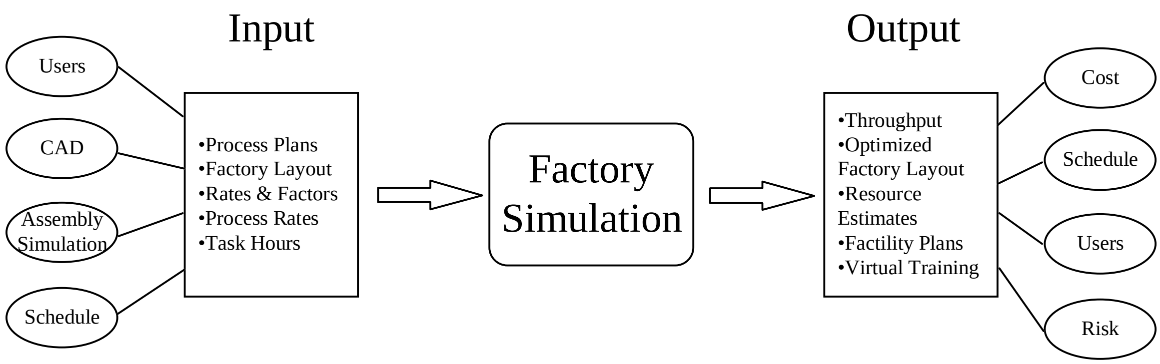


Figure 2-3. Factory Simulation Tool Interfaces

3.3 Virtual Assembly Planning

The virtual assembly planning tool uses associated product models and tool designs to produce assembly work instructions (or process plan) along with the hours associated with each task. This information is used in factory simulation, scheduling, and cost estimation. Figure 2-4 shows the top-level interfaces for a typical virtual assembly planning tool.

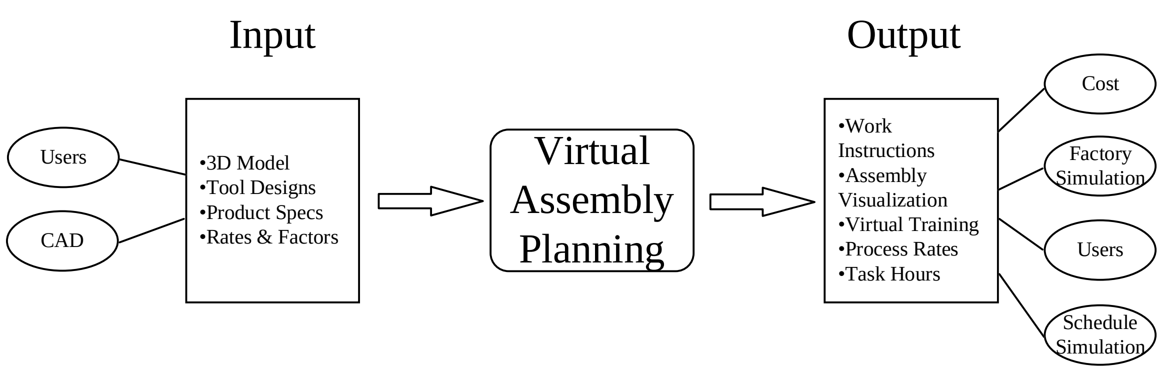


Figure 2-4. Virtual Assembly Planning Tool Interfaces

3.4 Schedule Simulation

The schedule simulation tool provides timelines and manpower analysis for a given set of work instructions. Primary inputs are provided by the factory simulation and virtual assembly planning tools with results used for cost and risk estimation. Figure 2-5 shows the top-level interfaces for a typical schedule simulation tool.

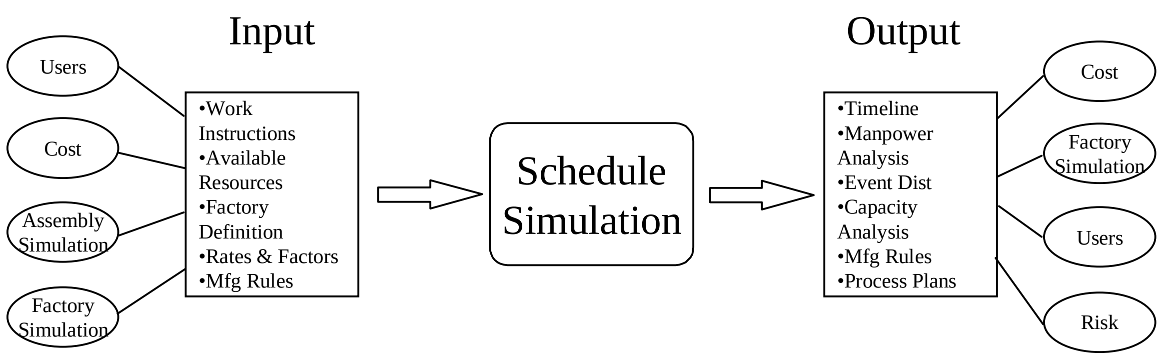


Figure 2-5. Schedule Simulation Interfaces

3.5 Cost Modeling

The cost modeling tool provides an estimate of the cost and producibility of a part containing a given set of features. The CAD tool provides the primary inputs for the cost model. This information, along with cost estimation models developed by users, provides the cost data, one of the primary drivers in assessment of a design alternative. Figure 2-6 shows the top-level interfaces for a typical cost modeling tool.

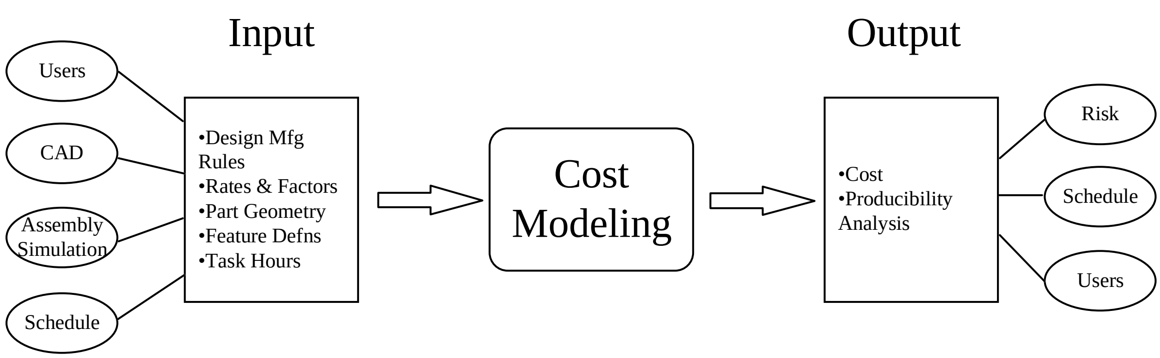


Figure 2-6. Cost Modeling Tool Interfaces

3.6 Risk Analysis

The risk analysis tool provides confidence profiles and uncertainty analysis for achieving a given set of parameters within a part or design study. Product definition, including tolerance and variability limits, are two primary inputs used in the risk estimation. Outputs from the risk analysis are used in the overall assessment of the design alternative. Figure 2-7 shows the top-level interfaces for a typical risk analysis tool.

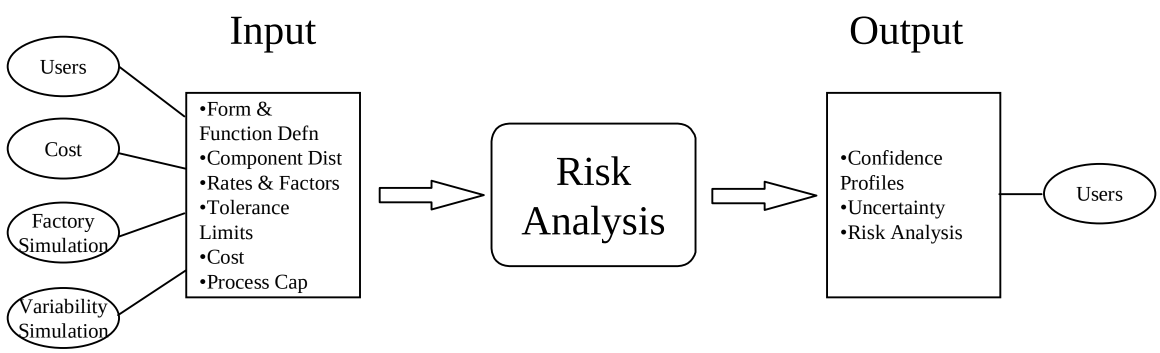


Figure 2-7. Risk Analysis Tool Interfaces

3.7 Assembly Variability Simulation

The assembly variability simulation tool uses CAD data, including features and tolerances, to make variability estimates for component and assembly distributions. This tool is tightly linked with the CAD tool and provides information to cost, schedule, and risk analysis tools. Figure 2-8 shows the top-level interfaces for a typical assembly variability simulation tool.

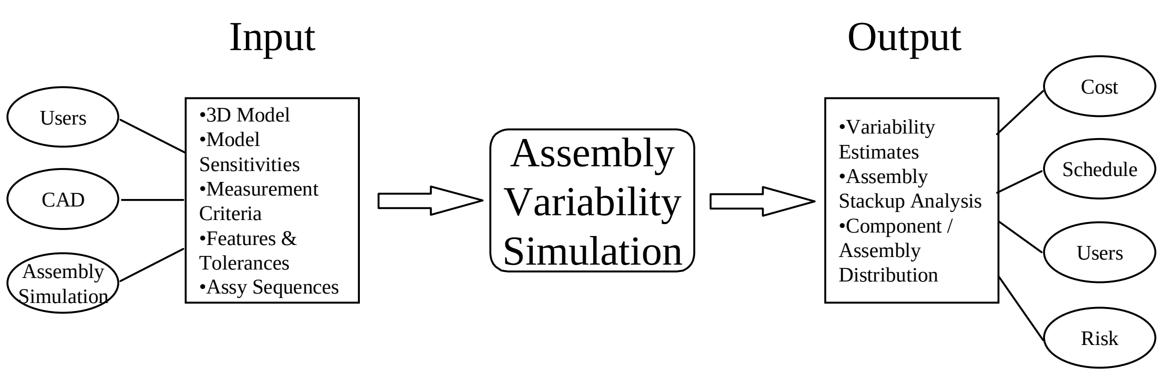


Figure 2-8. Assembly Variability Simulation Interfaces

4.0 Mechanism for Data Sharing

At the heart of the infrastructure is the SAVE Data Model (SDM), shown in Figure 2-9. It provides a mechanism for the classes of manufacturing simulation tools to share common data. The model was developed using both a top-down and bottoms-up approach with inputs from manufacturing engineers, design engineers, simulation software vendors, and simulation software users to ensure that all pertinent data were adequately represented. In keeping with the philosophy of wide review of the SDM, both programmer and user representations were distributed.

The SDM includes five general types of data: common; resource; product; assessment; and model management. Common data are the core of the model and provide information about the process plan and its operations. Resource data represent the information about personnel and tooling that is necessary to complete the process. Product data provide information about parts and materials and their relationship to the process. Assessment data are used to evaluate the

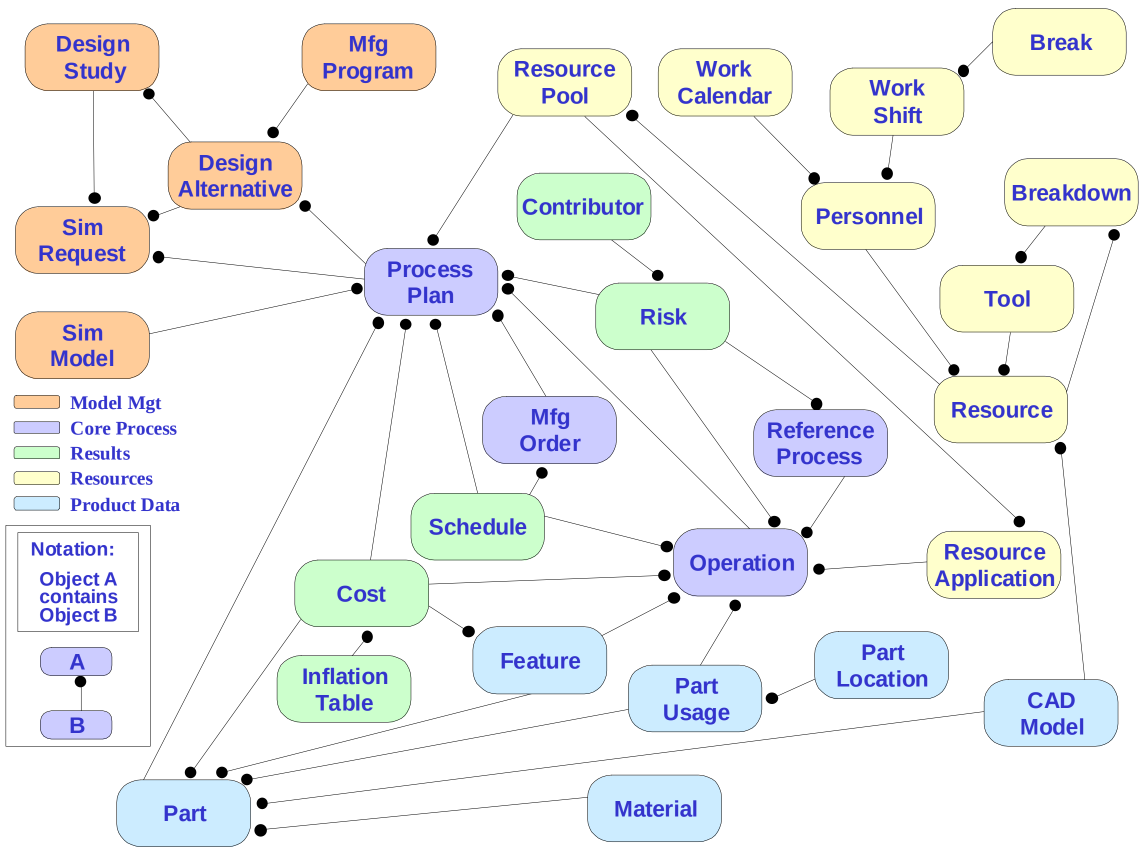


Figure 2-9. SAVE Data Model

relative cost, schedule, and risk of various alternatives in a design study. Model management data provides access and organization to the model. These components provide a robust mechanism for data sharing in the virtual manufacturing environment.

The SAVE model starts with a design study for a specific manufacturing program. The various alternatives associated with the particular design study are modeled and run through a series of simulations. At the heart of the model is the process plan that identifies the operations and resources necessary to manufacture a part. The plan and its associated part (or assembly) are assessed based on cost, schedule and risk at several levels of detail. Simulation results for these measures are compared and an alternative is selected as the preferred option for the design study. The model also allows for the situation where an assessment is desired for a single alternative.

5.0 Work Flow Manager

The SAVE architecture contains a Work Flow Manager (WFM) that provides graphical process modeling and execution. The SAVE team developed this software with strong influence from the DARPA Simulation Based Design (SBD) Program. It is implemented in JAVA to provide full platform independence. As depicted in Figure 2-10, the WFM software defines dependency relationships among the components of the process with decomposition down to the activity level. When the WFM executes, it has the capability to send messages to both users and tools,

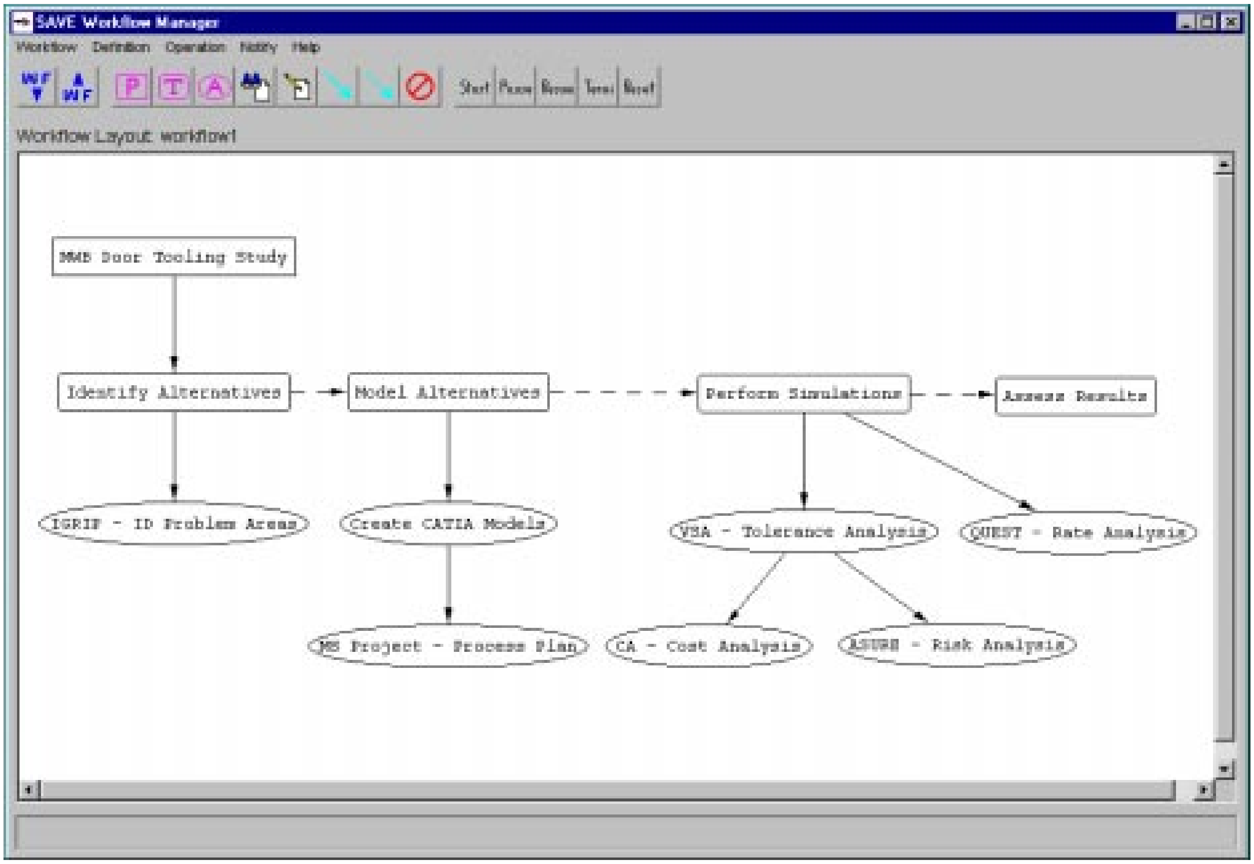


Figure 2-10. Work Flow Manager

monitor progress and status, and provide graphical feedback to the user. Details about the use of and integration with the WFM are discussed in the SAVE Software User Manual and Computer Software End Item documents.

Many of the manufacturing simulation tools within SAVE are interactive and do not run in a batch mode. The Work Flow Manager recognizes this fact and provides for an email to be sent to the correct user when an activity is prepared to run. When the user is ready, and has started the simulation tool, he uses the WFM to resume the paused tool.

6.0 Query Manager

In order to provide visibility into the SAVE data, the team developed a Query Manager (QM) application. This JAVA application provides the capability to browse, create, modify, and delete objects in the SDM. Figure 2-11 shows the screen layout for the QM. The left-hand side provides a tree structure of the library objects that exist in the model, whereas, the right-hand side displays attribute data for a specific object within the tree.

The SAVE QM does not interface directly with either the simulation tools or the WFM. Its sole purpose is to provide access to information in the SDM through a mechanism other than the simulation tools within the SAVE toolsuite. The Query Manager User’s Guide, included in

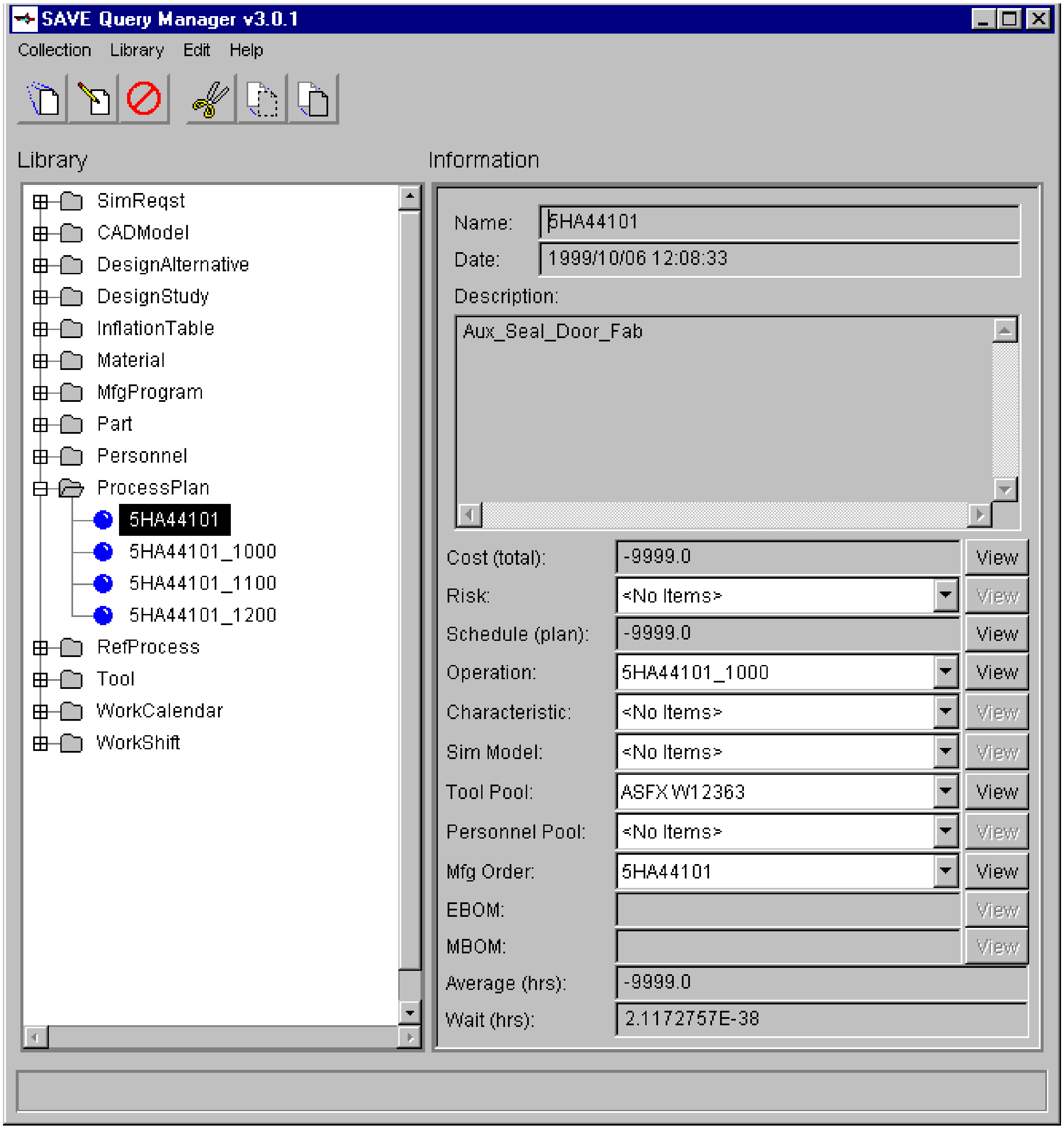


Figure 2-11. Query Manager

Appendix M of the Software User's Manual, provides detailed instructions for use of the QM application.

7.0 Electronic Design Notebook

As an added feature for the Integrated Product/Process Team (IPPT) the SAVE infrastructure provides for an electronic collaborative design notebook (EDN). This notebook allows team members to share information and coordinate with each other during the execution of a design study. The electronic notebook maintains a user captured, annotated record of the design as it progresses. The record can include audio and video clips as well as snapshots from the document under consideration. This data can be used by the manufacturing engineer or designer in evaluating and preparing fabrication and assembly instructions.

In Phase I, SAVE used an EDN application that was developed as part of the DARPA DICE and SBD programs. As web technology progressed and became more widespread, the team shifted to Netscape's Collabora product. This application, shown in Figure 2-12, works like an internet newsgroup with threads and postings within the SAVE study being conducted. SAVE does not, however, restrict product selection, so there may be other commercial products that also satisfy the EDN requirement.

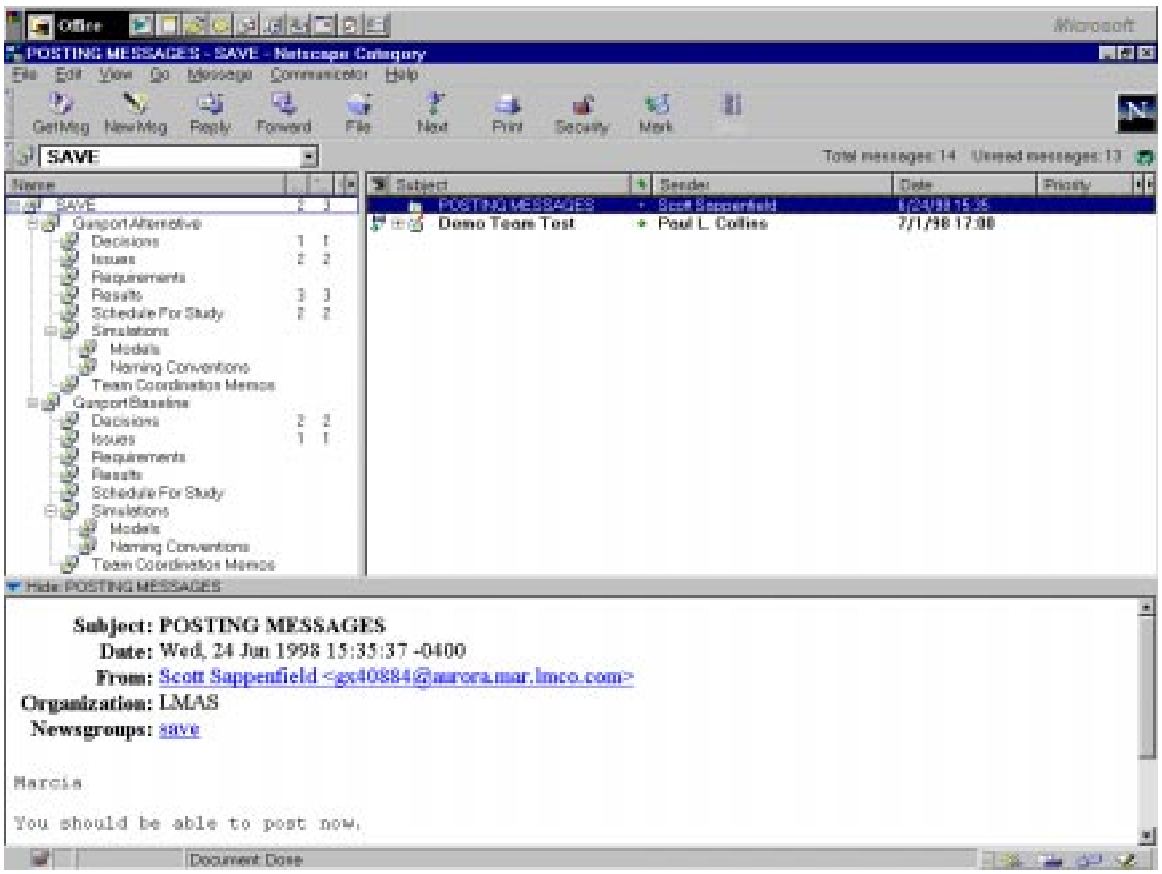


Figure 2-12. Electronic Design Notebook (EDN)

8.0 Use of Common Object Request Broker Architecture (CORBA)

Alone, the components of SAVE can be expensive to use, so integration is a key element of the infrastructure. The SAVE team selected the Common Object Request Broker Architecture (CORBA) standard to provide this integration by allowing the components of SAVE to communicate with one another without point-to-point interfaces. This concept is shown in Figure 2-13. The CORBA standard was developed by the Object Management Group (OMG) and provides middleware functionality for integrated distributed systems without regard for

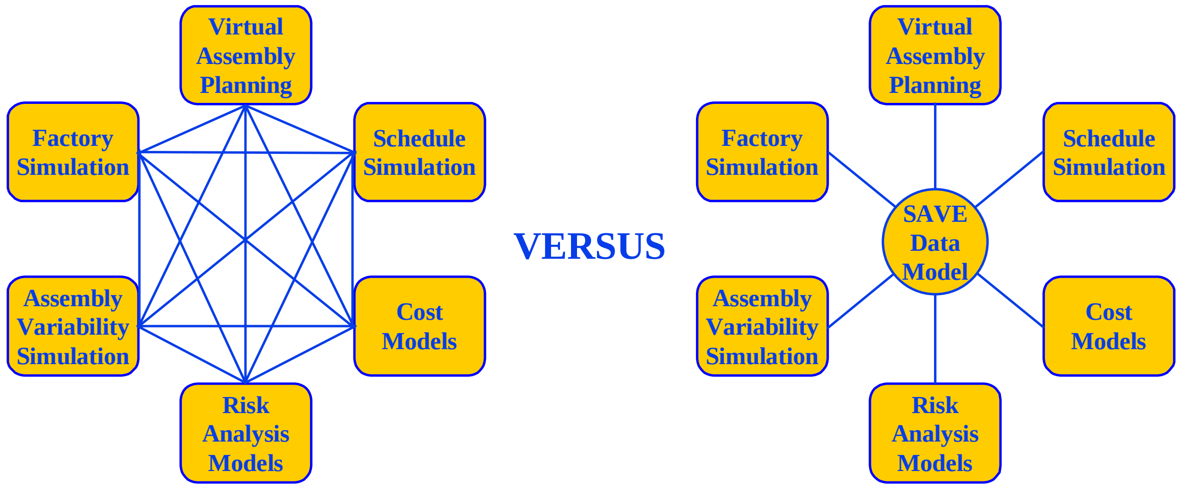


Figure 2-13. CORBA Interface Approach

platform, protocol, or language. The CORBA architecture is depicted in Figure 2-14 and has two primary components: Interface Definition Language (IDL) and Internet Inter-ORB Protocol (IIOP).

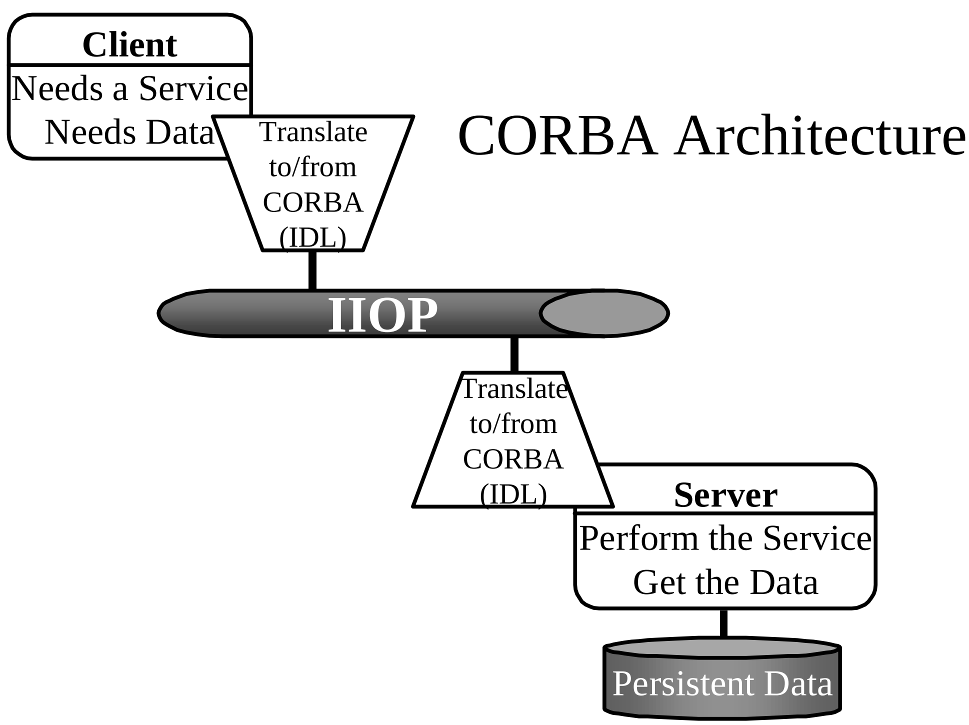


Figure 2-14. CORBA Client Server Application

IDL provides a language independent object specification that translates between the client and server. For SAVE, the IDL serves as the "contract" for data exchange within the infrastructure. IIOP provides transparent, distributed communication so that objects located anywhere on the network can communicate with one another. For SAVE, IIOP allows clients, servers, and data storage locations to be distributed across the IPPT's computing network.

The strategy for effective use of CORBA within the SAVE program involves creating an IDL that is based on the SAVE data model and distributing that IDL to tool vendors interested in developing an interface into the SAVE environment. The data model and IDL are documented in the SAVE Computer Software End Item document.

Integrating a new virtual manufacturing code to operate within SAVE involves wrapping for infrastructure support and wrapping for data integration. Approximately 40 person hours are required to interface with the infrastructure. Effort to interface with the object-oriented data model varies with the amount of input/output required but is estimated to require 200-300 person hours.

In general, there are two types of CORBA interfaces within the SAVE infrastructure. The first is a tool data wrapper that allows the manufacturing simulation tools access to information within the SDM. These wrappers facilitate data sharing among the tools. The second type of interface provides communication between the WFM and the manufacturing simulation tools. Using this interface, the tools can accept inputs and commands from the WFM as the process executes. Both of these interfaces are developed only once for each tool that is integrated into the SAVE environment. Changes to these interfaces will be required as the SAVE data model is expanded, but less maintenance will be required than with traditional point-to-point interfacing. As additional tools are added or data storage locations change, the interfaces will continue to operate without modification. The CORBA interfaces for the SAVE manufacturing simulation tools were approximately 80% complete as of the final demonstration, lacking a small amount of functionality and production-level software testing. Following the final demonstration, the tools were upgraded and tested with the commercial-grade SAVE server that was developed by Cognition Corporation. Potential users can contact the tool vendors for specifics on the status of their SAVE-compliant tools.

Using the CORBA architecture also provides flexibility in the back-end data storage for SAVE. The SAVE server, the CORBA representation of the SDM, can physically store data in any one of many data storage facilities. This approach allows user sites to customize data storage to meet their own needs. These facilities may be company specific and include object-oriented databases, relational databases, product data managers, and others. The current SAVE infrastructure uses Object Store, an object-oriented database, to store all information represented by the SDM.

The SAVE team conducted a parallel study to test the back-end connectivity with a relational database. A sample database that contained part information was constructed. The SAVE server was modified to retrieve certain part attributes from that database. The system was tested with the existing Query Manager application to validate the link and its transparency to any client application. The activity was quite successful and provided useful information for implementing a more complete capability. Two key issues include the need for references or back pointers to parent objects in the SAVE model and the need for a utility to simplify the mapping between the SAVE object oriented schema and the relevant relational schema.

9.0 Approaches to Client Data Access

In general, any simulation tool that is SAVE compliant will access the database in two separate transactions during its execution. Prior to simulation execution, a read transaction will be used to access the data needed as input to the simulation. This read transaction is non-blocking, that is, one update transaction and other read transactions may occur simultaneously. The read transaction will end when all input data has been read. When a simulation is complete, an update transaction will be initiated to place new data into the database. If another update transaction is in progress, this request will wait until the first is finished. It is estimated that this wait will be less than one minute in length. Once an update transaction is initiated, new data will update appropriate objects in the model, and the transaction will be completed with a database commit.

The SAVE IDL includes a database object that contains methods for database transaction control, commits or rollbacks, and a general object search capability. This database object contains no data and is not stored in persistent storage. It is easily declared in the client code, making its methods available to the client.

In most cases a client will not need the general search capability. The SAVE workflow manager will launch a simulation code that has been wrapped as a SAVE client and will pass a reference to a particular locator object in the data model. This locator will have the required design study, design study alternative, and process plan for which the simulation run is to be made. These object pointers are sufficient to access all related data within the model.

Within the SAVE data model, most data variables are directly accessible for either read or update. A few variables must be updated through methods to assure consistency. The versioned variables in cost, schedule, and risk information are examples of these.

During update operations, the SAVE server will automatically assign date/time stamps to assure consistency. When updates are complete, a commit command may be given (or rollback if there was a problem), and the transaction ended.

10.0 Approaches to Client/Server Development and Deployment

One important factor in designing the SAVE architecture and tool integration approach is its viability as a commercial product. There are essentially two components to the commercialization of SAVE—tool interfaces and server implementations.

It is envisioned that tool vendors will provide a commercial offering of their “wrapped” tool. With the use of CORBA, these interfaces will be stable and supportable. To date, all SAVE team vendors have expressed strong support for commercializing SAVE, dependent, of course, on customer interest.

There are a number of viable approaches to commercial server implementations. With any approach, a vendor will provide a server that complies with the IDL for the SDM and will develop links to the customer-desired data storage mechanism(s). The SAVE team has developed a “conventional” server based on C++ with ties to an object-oriented database. One SAVE vendor, Cognition Corporation, used their Knowledge Center (KC) product to provide a SAVE-compliant server with an object oriented database back-end. The “conventional” server and the KC server work with any of the SAVE compliant clients without the need for client modifications. This is possible because both servers and clients use the SAVE IDL as a “contract” for their interface requirements. As long as each server and client complies with the IDL, the pieces are interchangeable.

11.0 Configuration Management Capabilities

The nature of complex product design is inherently iterative and SAVE has been designed to manage the multi-version nature of design simulation data. As a design tool, SAVE-generated data are expected to be released (likely controlled by a PDM) to production and transferred to downstream systems. SAVE provides configuration management of data while it is in work, provides for data storage by a PDM, and allows results to be extracted to downstream systems if the data are not already stored there during development.

The philosophy behind SAVE data management is to provide flexible control that can be tailored by a design team. SAVE developers and users must develop an understanding of SAVE’s Data Model and the data configuration management capabilities it provides. This understanding will allow a team to quickly identify the paths to be included in a design study and the best representation of the data within SAVE.

The elements of SAVE configuration management include:

- Status Flags – Included with several key data elements - lower level data controlled automatically
- Alternatives – Supported for Design Studies and Process Plans
- Copy Command – Intelligent copy of Process Plan to start alternatives
- Remove/Delete – Tracks references to data objects by other objects
- Versioned Variables – Minimizes need to create alternatives
- Back End Data Storage – Data management of physical storage system.

Each of these elements and their use are discussed in detail in the SAVE Computer Software End Item document.

12.0 Computing Environment

SAVE has always supported a distributed, heterogeneous computing environment. The architecture and tool integration approach allows tools to operate on any platform the tool vendor supports using any programming language supported by or interfaced to CORBA. Table 2-3 lists the hardware platforms, operating systems, and software tools that have been supported during the course of the SAVE program. Items in italics represent the SAVE configuration as of the final demonstration.

Table 2-3. SAVE Computing Environment

Hardware Platform	Operating System(s)	Software
PC	*NT*, Windows 95, Windows 3.1, OS/2	*Factor AIM, ASURE, Cost Advantage, WFM, QM, Server, EDN, Orbix, Orbix Web, MS Project, Wingz*, JMCATS, MECE
IBM RS6000	*AIX* Various Versions	*CATIA, VSA3D, EDN, Orbix*, Cost Advantage
Silicon Graphics	*IRIX* Various Versions	*QUEST, IGRIP, ERGO, EDN, Orbix*, Cost Advantage
Sun SPARCStation	Sun OS	RASSP
Macintosh	Mac OS	ASURE, Wingz

13.0 Team Communication

With any team, but especially with a geographically disperse team, communication is a key element to the ultimate success of the team's activities. The SAVE Tool Integration and Architecture team was highly distributed with members at vendor and Lockheed Martin companies across the country. One lesson learned early in SAVE was that the team needed to improve its communication in order to increase its productivity. In order to address this lesson, the team enhanced written documentation, increased the number of face-to-face meetings, and conducted telephone conferences on a regular basis. During each phase of the program, the team followed a sequence that worked quite well.

At the beginning of a new demonstration phase, members of the SAVE IPTs including representatives from each vendor met to discuss specifics of the upcoming demonstration phase. Overview discussions were held for the demonstration, tool integration and architecture approaches. These presentations afforded each vendor representative the opportunity to comment on individual ideas and concerns relative to the planned approach for that phase.

This feedback was incorporated into the written specification documents that were typically published a month or two after the meeting with wide distribution to the SAVE team, the OTF/TBAB members, and the SAVE customer community. The specifications included the Architecture and Tool Integration Specification, the Demonstration Description, and the Concept of Operations.

The Architecture and Tool Integration Specification document was the primary written guideline for the team. This document specified the methodology for sharing and exchanging data among the SAVE tool suite. The tool vendors used this specification for developing the software interface required for communicating within the SAVE framework.

With the specification documents available, representatives from the SAVE Architecture, Demonstration, and Tool Integration IPTs conducted a tour that included visits to each tool vendor site. The purpose of these meetings was to discuss the specification documents in detail with respect to the needs and requirements of each individual SAVE tool vendor—Deneb, EAI, Symix, SAIC, and Cognition. Results from these meetings were documented in meeting notes and sent to the team members. These results included required modifications to the specification documents, data model mappings for the vendor tools, action items for clarification of requirements and responsibilities, and general discussion of the approach for using the tools during the upcoming demonstration.

Using the results from these meetings, the specification documents were updated. The updates typically included expansions and clarifications that were identified during the vendor meetings as well as feedback from other reviewers. These updated documents served as the basis for tool interface development during that phase.

Once the actual code development started, the team conducted weekly telecons to discuss any development issues that were of interest to the majority of the team. These telecons, along with e-mail mailing lists, kept the team informed of critical technical information, allowed for technical exchanges among the entire development team, and provided visibility into any possible problems with meeting the development and delivery schedules for the software.

When important issues were identified, members conducted separate, topical telecons that addressed only a single issue. At times, experts were asked to join the telecon to provide additional insight into potential solutions. These minutes from these conferences were documented and sent to the team via e-mail with instructions on the recommended course of action. When telephone and e-mail communication was insufficient to resolve the issue, the team met at a single site to further address and achieve resolution.

The team also had two resources available to download or access pertinent information. The SAVE website was kept up-to-date with programmatic and training data. In addition, the Tool Integration IPT established an FTP site to facilitate communication and data exchange. The core development team in Marietta maintained the site with each team member having access to the types of information listed below:

- Documentation
- Specifications
- IDL
- Sample Client Source Code
- Server Source Code
- Software Executables
- Utility Applications

Once the software was delivered to the user site, a core group would travel to that site to aid in the installation and verification process. In most cases, it was necessary for each vendor to have a representative on site to provide hands-on expertise for troubleshooting their software. Once the software was successfully installed, the team provided telephone and e-mail support for the user site administrators.

The combination of in-person meetings, telecons, e-mails, and written documentation improved the SAVE tool integration and architecture team communication and effectiveness allowing them to successfully develop the SAVE virtual manufacturing environment.

Chapter 3

Design / Cost Integration

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 Overview

The cost estimating tool within SAVE extends the capability of similar traditional methods by integrating outputs from both manufacturing simulation and CAD tools. This provides a more robust cost estimate that is based on both design features and the manufacturing processes of the component. In addition, business costs inputs and program expertise in the models help provide cost and producibility guidance to the IPT. This integration for the cost estimate is described in Figure 3-1.

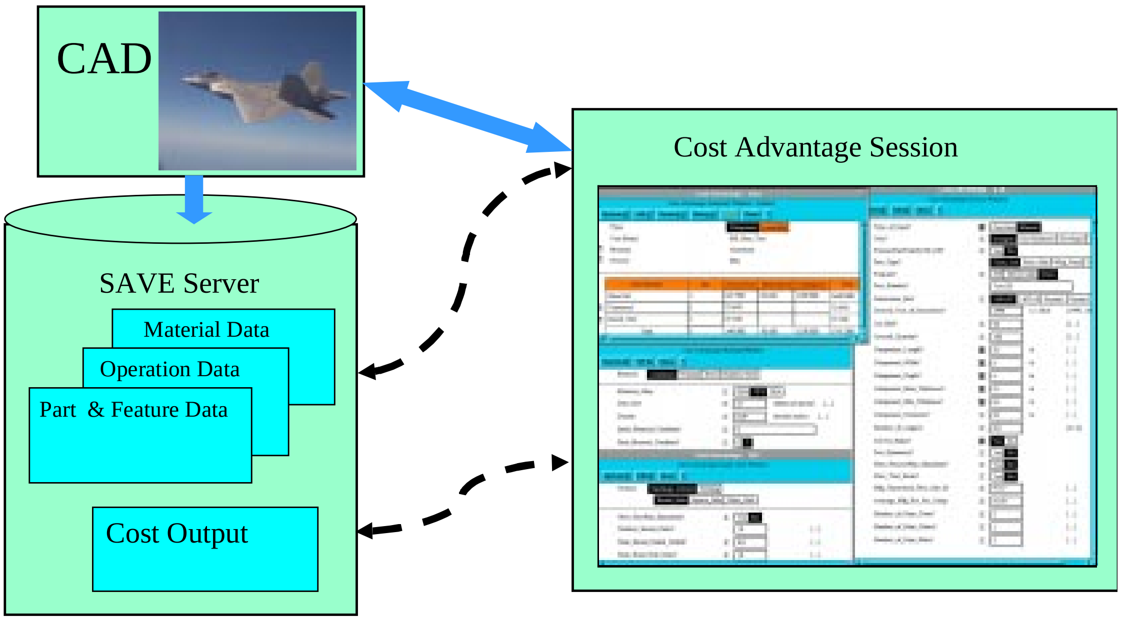


Figure 3-1. Data Shared Among Cost Module, CAD, and SAVE Server

A key aspect of this cost estimating method is its capability to relate product features to manufacturing processes. Each company can customize its cost model to add features that are cost drivers in its manufacturing environment. Since this cost tool is designed with-in a cost estimating based expert system shell, a company's specific cost algorithms, help screens, and rules can also be added. Figure 3-2 describes top-level inputs and outputs of the cost estimating system. Both automated SAVE system inputs and cost estimator user inputs are utilized. The output is an estimate of the cost of producing the part or assembly.

The SAVE Cost Modeling System is built on the Cognition Corporation's Cost Advantage™ product. It is comprised of a series of knowledge bases that are used to define cost and producibility rules for manufacturing processes. These rules are based on information about manufacturing processes and product features. Four cost models were developed for the SAVE program. These were utilized in demonstrations and delivered to Cognition for commerciali-zation. The following Cost Advantage™ (CA) models were built for the SAVE program:

- Assembly
- Sheet metal
- Numerically controlled (NC) 5 Axis machining
- Hand lay-up composite parts.

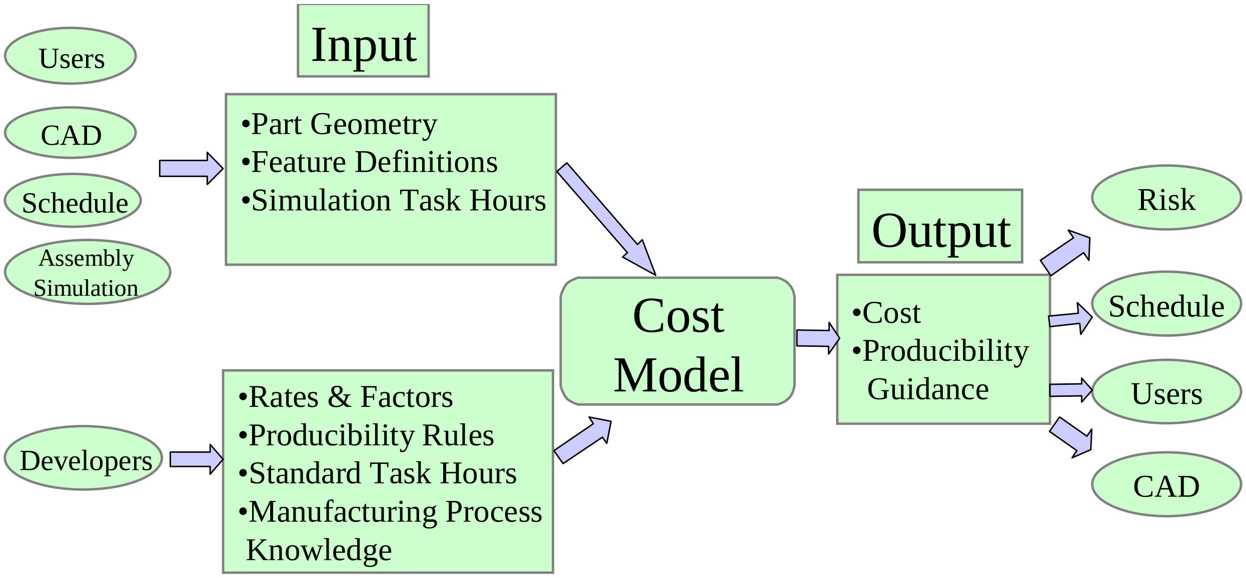


Figure 3-2. SAVE Cost Model – Input and Output

Typical inputs and outputs associated with the four SAVE cost models are described in Section 4. The models can be customized to reflect individual company business practices and reporting requirements. Representative operations and cost estimating relationships (CERs) are included as a starting point for future development.

Each of these cost estimating models rely on the CAD feature extraction capabilities provided by the CAD-to-cost-model tool, CostLink, partially developed under this program. This capability was included in the final demonstration for both parts and assembly features. Process plan, cost, and manufacturing simulation data were extracted via a wrapper to and from the SAVE database.

2.0 Objectives

The objective of the Enhanced Design/Cost task was to develop tools and methods for integrating design and process information into a cost estimating tool. Previously, design data had to be manually extracted from a drawing and hand entered into the cost model. There were no cost models that could handle the feature based design data automatically. Nor was there a means for automatically obtaining design data and process information to support the Integrated Product Team's decision making process.

The SAVE team developed a link between the CAD tool, CATIA™, and the Cost estimating tool, Cost Advantage™. Generic knowledge bases for a select set of manufacturing and assembly processes were built and populated. Access to and from the SAVE database was also developed to handle cost outputs as well as manufacturing process plan and simulation information.

This task focused on:

- Integration of design tools (CAD) with a cost prediction tool that could enable feature-based process-oriented cost modeling

- Development and validation of design/cost knowledge bases to support cost and producibility assessments

- Development of an implementation and commercialization plan to insure transfer of technology to industry and the JSF Program.

The interrelationships between design and manufacturing methods and their impact on cost was identified as a critical element to meeting affordability goals for the next generation fighter (JSF). A primary objective for the cost estimating task was to increase the fidelity of models by utilizing feature and process-based thinking which could more easily reflect business improvements and initiatives.

These objectives were showcased in the Phase I and Phase II demonstrations. The multi-phase approach provided opportunities to implement lessons learned from initial development work into the final product. This assured greater success in supporting the SAVE program commercialization goal.

3.0 Approach to Integrating Design and Cost Tools

A multi-phase approach was successfully utilized in the Design/Cost tool integration task. The cost-estimating relationships in our cost models were developed utilizing key design features and manufacturing processes. The SAVE tool provided the capabilities to automatically acquire the feature and process information necessary to provide a good cost estimate. Phase I included significant hard coding of design feature definitions and their interfaces to cost and manufacturing features. As a result of this, Phase II resulted in a more useful, generic product. Lessons were also learned in developing cost estimating models, which were incorporated into the sheet metal and assembly cost knowledge bases.

The following Section briefly describes the cost tool integration with the other SAVE tools and CATIA™. Phase I, Interim Phase II, and Final Phase II activities and results are discussed in Section (3.2). A brief description of implementation issues and users are included in Sections (3.3 and 3.4). Feature based costing is a key ingredient of the SAVE cost estimating environment and is described in Section (3.5). Commercialization and integration plans are discussed in the last Sections of (3.6).

3.1 Cost Tool Integration Within SAVE

The uniqueness of the SAVE cost models is their capability to integrate with design and simulation data. This section briefly describes the capabilities of these two functions. More detailed descriptions are included in the SAVE Software End Item Description and User's Manual documents.

3.1.1 Integration Between the CAD Tool CATIA™ and Cost Advantage™

The CAD tool used for demonstration by SAVE is CATIA™, a 3-dimensional design tool widely used by aerospace companies. (Other CAD tools are easily integrated into the system.) CAD provides part, assembly, tool, inspection equipment, and support equipment designs as well as data for numerically-controlled (NC) programs. The CostLink software developed by

Cognition Corporation for SAVE extracts pertinent design information from CATIA™ and makes it available to the cost estimating session. The data is stored in the Cognition Corporation tool Knowledge Center™ (KC) and is imported into the cost estimating session in Cost Advantage™. The designer can access Cost Advantage™ from a CATIA™ session, or the cost estimator can access previously saved design data for inclusion in a trade study. See Software User Manual Appendix I CATIA™ CostLink User's Guide for more information.

3.1.2 Integration Between Cost Advantage™ and the SAVE System

For integration between Cost Advantage™ and the SAVE system, a map file is used which correlates the variable names in the cost model with those used in the SAVE database. More information on this topic is available in Software Users Manual Appendix E, the Cost Advantage™ Wrapper User's Guide. This integration provides the capability of accessing process plan data which can be utilized in the cost estimate. Another advantage is the ability to acquire labor hours from the manufacturing simulation to more accurately represent certain operations. Other risk and tolerance data can also be passed into Cost Advantage™. Additionally, cost results are seamlessly transferred back to the SAVE database for analysis and reporting.

3.2 Program Tasks and Results

3.2.1 Phase I Results

Deliverable products completed in Phase I of the SAVE program consisted of two cost models and a cost link between the Cognition Cost Advantage™ software product and Dassault's CATIA™. The cost models addressed Numerical Controlled (NC) machined and composites hand lay-up process knowledge bases to predict cost for a specific structural geometry class. The cost models developed, although limited in scope, successfully demonstrated a capability to generate total manufacturing costs. They specifically captured which activity costs vary with a unique cost driver in relation to geometry and the process method and to what degree those costs vary. The SAVE team also investigated the feasibility of using the SAVE infrastructure technologies to integrate with legacy systems by working with the F-22 Production Cost Model team to determine requirements for sharing information.

3.2.2 Phase II Interim Phase Results

During the Phase II interim cycle, the metal and composite fabrication models were enhanced, the Phase I assembly model was expanded, and a new sheet metal model was developed. The cost link software was turned over to Cognition Corporation for further development and commercialization. This resulted in a significant rewrite and expansion to support the Interim Demonstration.

The work performed in Phase I of this task was tested by several JSF program Designers. Their feedback regarding the cost models' operability, look and feel, and the input/output screens was used to plan the changes and/or extensions for the Phase II deliverable items for this task. The models were constructed to be extensible to include both preliminary and detail level design data to meet the designers needs.

3.2.3 Phase II Final Cycle Results

During the Phase II Final Cycle, the Assembly model was significantly enhanced to include additional processes and capabilities. Additional sheet metal functionality was developed utilizing learning from the Composites Affordability Initiative sheet metal model. The CostLink was upgraded and expanded to provide a more generic Feature based functionality. In specifying the Phase II CostLink, talks were held with Cognition and several non-SAVE users to determine the optimal approach. This supported the commercialization end goal. A commercial version of this CostLink software is now available.

3.3 Approaches for Implementing Design/Cost Tool Integration

There are several facets to implementing a cost estimating tool into an integrated environment such as SAVE. These include identifying product families, understanding their cost driving features, identifying relevant manufacturing processes, and developing associated cost estimating relationships. The developers also need to work closely with their ultimate system users and data sources to ensure the best models and end-user buy-in for the system.

The first step towards implementing the SAVE cost estimating system is to work with the cost estimators, designers and manufacturing personnel to identify the components that are most beneficial to include in the system. Next, identify the cost driving features of these part families and relate them to your manufacturing processes. In-depth research is then required to define manufacturing planning performed at the factory, limitations of the equipment, material specifications, time standards, and cost factors.

Resources for performing this development task include:

- Manufacturing Engineers
- Process Experts
- Producibility Engineers
- Textbooks and Handbooks
- Industrial Engineers
- Value Engineers or Cost Estimators
- Finance Personnel
- Tool Designers

Once the research is complete, the next phase is design. This encompasses the establishment of variables and the designation of variable location within the cost tool. Relationships to a SAVE compliant database are also established here. The next phase is to program the variables and cost estimating relationships (CERs) into the cost tool utilizing templates like those developed under the SAVE contract. Once this phase is complete, a validation activity is required to make sure the information is reliable. It is important to include the end users in these activities so that they will be comfortable with the features and CER approaches that are selected.

Cost Advantage™ contains three variable categories: material, process, and feature. The cost and design characteristics are allocated into these three areas. A typical developer’s screen is shown below in Figure 3-3. Cost estimators or value engineers are typically the ones who will be implementing the cost estimating relationships into this tool. A producibility engineer or

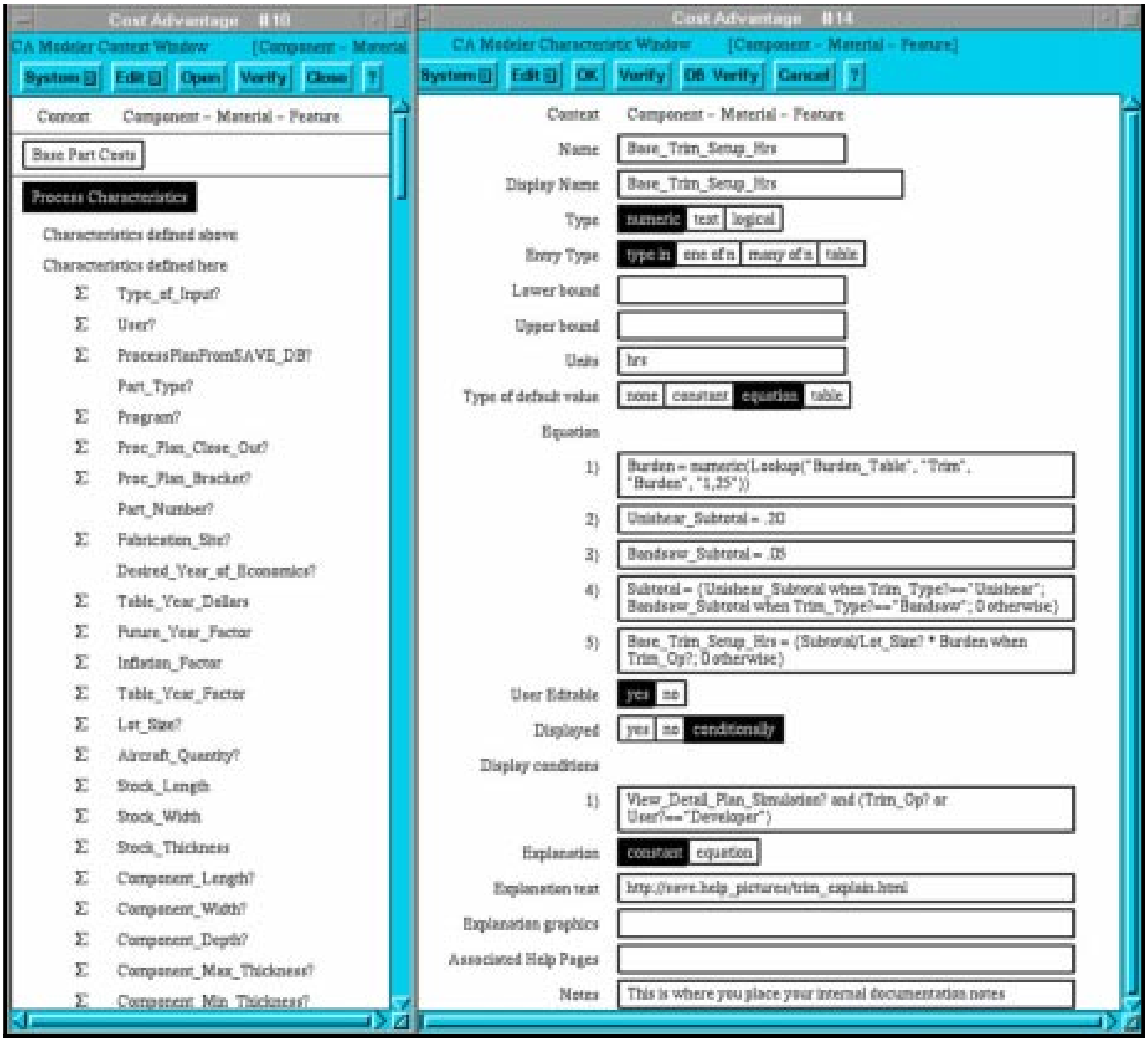


Figure 3-3. Cost Model Developer Screen Example

manufacturing engineer will provide producibility rule support. It is critical to document the model with comments about the CERs and producibility guidance. Cost Advantage™ provides the capability for the developer to record internal notes regarding each object or formula. Other help information can be documented for access by the end users. This help can be embedded in the cost tool, located in external files, or accessed from the web. The user can easily access this information while working on the cost trade.

Both cultural and political issues need to be considered when implementing an expert system cost model such as the SAVE tool. Agreement is required by all affected departments for this tool to be accepted and utilized. This is a new way to do business for many companies, so this acceptance is critical to the success of the program. This cost tool provides the Integrated Product Team (IPT) a way to rapidly do design trades that include cost. The designer could potentially use this tool on his own, although this should only occur for straightforward trades. The bounds for a designer using this tool without a cost estimator need to be understood and agreed to by all groups. The ideal situation for using this tool is for the designer and cost estimator to sit together and utilize the SAVE cost tool during their design trade.

An example of the type of information that the end user would see when utilizing the SAVE cost tool is shown in Figure 3-4. Both inputs and outputs are readily accessible during the trade study. The user can also query the system for help during his session. When implementing the system, the developer should work with the end users to ensure that the appropriate information is presented on the user's screen.

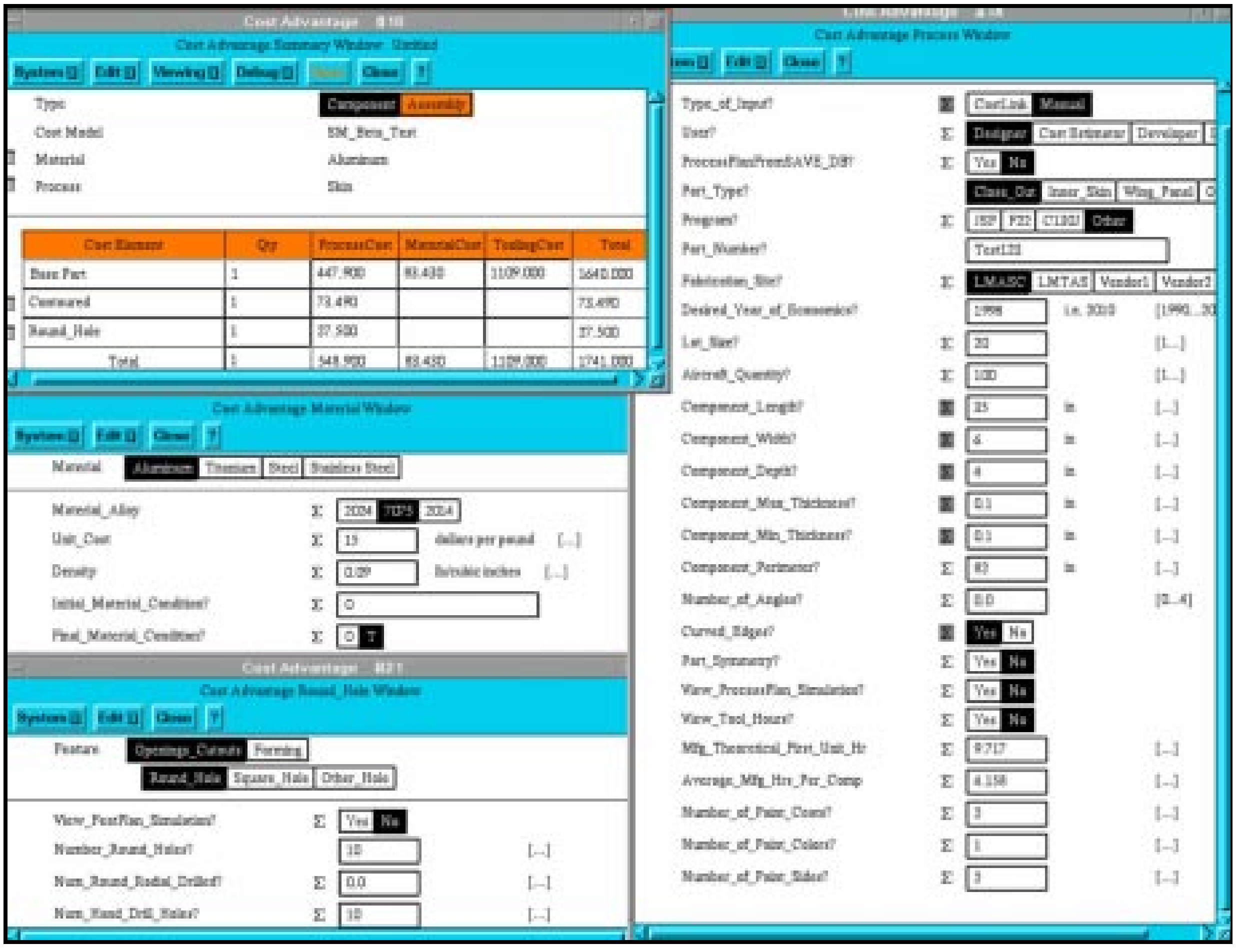


Figure 3-4. Cost Advantage™ End User Screen Example

There are several things that can be done to maximize the benefit and usefulness of the system. First, training is very important for both the users and developers. Secondly, system maintenance is required to avoid the potential problem of data obsolescence. Developing a plan for updating the CERs when the factory and products evolve can resolve this. This plan should include a scheme for material costs and labor rate updates.

More information on this topic is available in the Software Users Manual Appendix E, the Cost Advantage™ Wrapper User's Guide.

3.4 System Users

The SAVE Cost Advantage™ tool will be accessed by multiple members of the team. Each person will have a different viewpoint of what data he wants to see. For example, the cost estimator, who is the primary user of the system, will develop cost estimates for the design trade using both the expert knowledge embedded in the system and his personal expertise. She may also be modifying learning curve factors and labor rates and factors.

The design engineer will utilize the system to obtain a quick look at the cost impact of his design when it is within the bounds of the cost model. This may occur for derivatives, and conventional parts. The CostLink allows the design study team to automatically input relevant CAD data into the cost model. Figure 3-5 shows the diversity of users interacting with these cost estimating models, both through supplying information for developing cost estimating relationships to the developer and as end users. The team is able to do what-if cost trades to support their design decisions.

Labor rates and factors will also need to be updated. The Cost Estimating or Value Engineering departments are typically responsible for model updates to reflect changing environments and manufacturing processes. They will obtain information from many other organizations and sources such as Industrial Engineering, Tool Engineering, Finance, Planning, and Design.

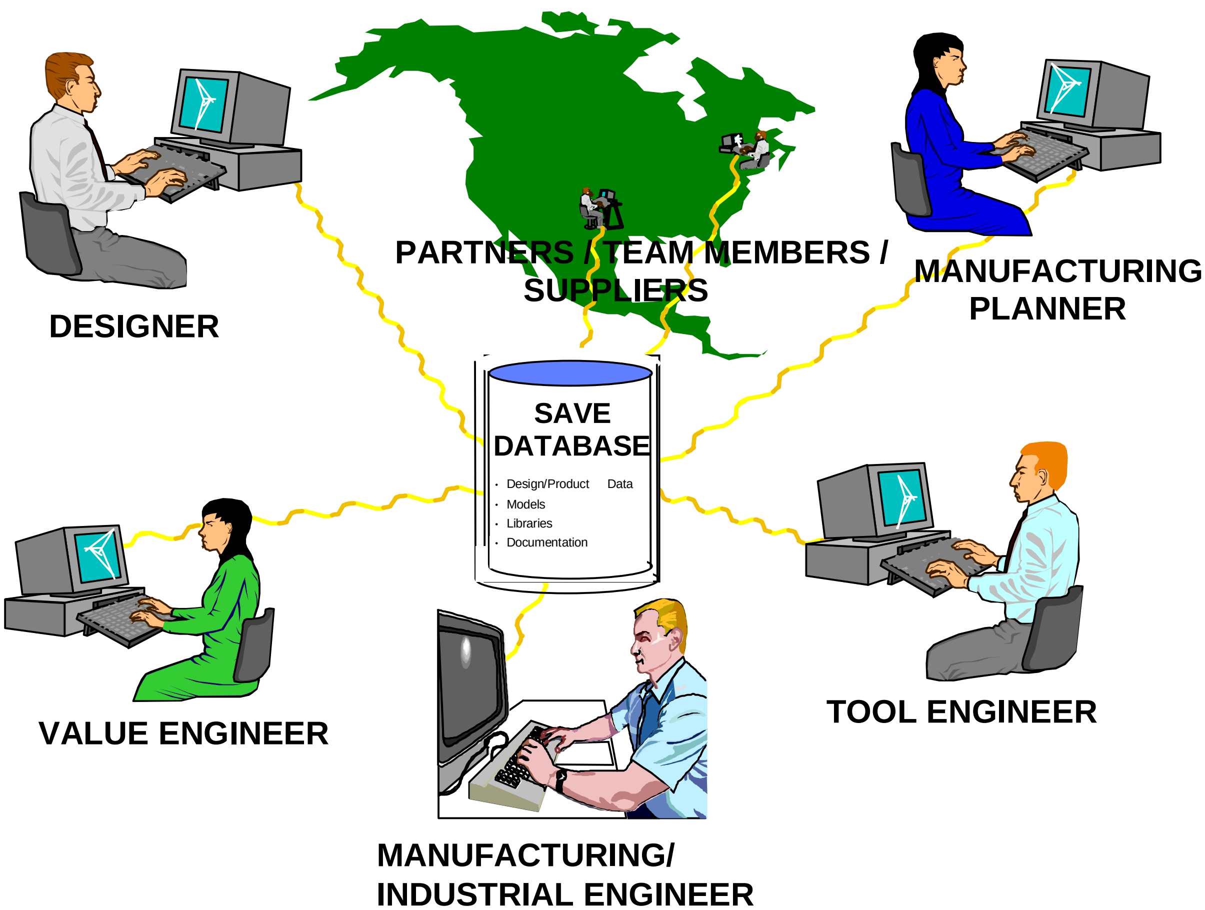


Figure 3-5. Personnel Resources Required for the SAVE Cost Model

Additional information on how to update a cost estimating model is included in the Cost Model Development Guide, Chapter 6 of the Software End Item Document, as well as in the Cost Advantage™ User's Guide. The SAVE cost models are designed so that a company can add in its own proprietary relationships and data.

Typical information that would be modified by the developer includes:

- Proprietary cost estimating relationships (CERs)
- Additional or modified manufacturing processes
- Labor rates and factors
- Inflation factors
- Proprietary default values for variables
- Additional design features and characteristics.

The Cost Advantage™ cost estimating tool is designed as an expert system shell. This allows the cost estimator/developer to modify the existing SAVE models to reflect their own business practices and environments. The syntax for the developer's environment is straightforward, as shown in Figure 3-3, so modifications to an existing model are very easy for a computer literate, experienced cost estimator to make.

3.5 Feature Based Costing Overview

The SAVE program utilizes feature-based cost estimating models. These cost models use the relationships between design features and manufacturing processes to provide cost information about the component or assembly. Each part family will have different key cost driving characteristics that are defined by the IPT. A sheet metal part and its features are illustrated in Figure 3-6. Many of these part features are common to the composite part illustrated in Figure 3-7. When the SAVE cost models were developed, common features were implemented for the machined and hand lay-up composite parts. Lessons learned were implemented in the cost knowledge base.

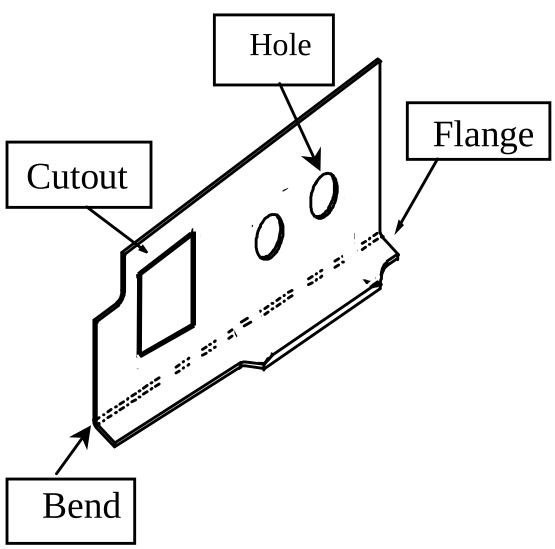


Figure 3-6. Cost Driving Features for Machined Part Example

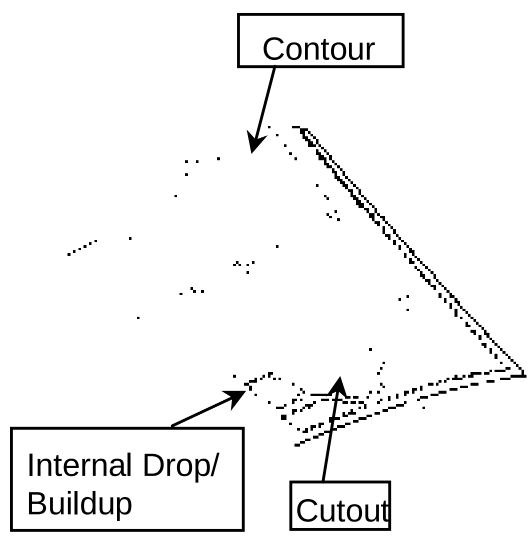


Figure 3-7. Example of Hand Lay-up Features

The following are examples of features and part characteristics common to many cost estimating knowledge bases:

- Component length and width
- Component thickness – minimum and maximum
- Hole diameter and tolerance
- Contour
- Material type and form

Additional features that are only found in composites, such as numbers of plies and buildups, can be written into the composites knowledge base. The relationships of these features must be integrated into the costing methods. Figure 3-8 shows some process feature relationships from the machining cost model.

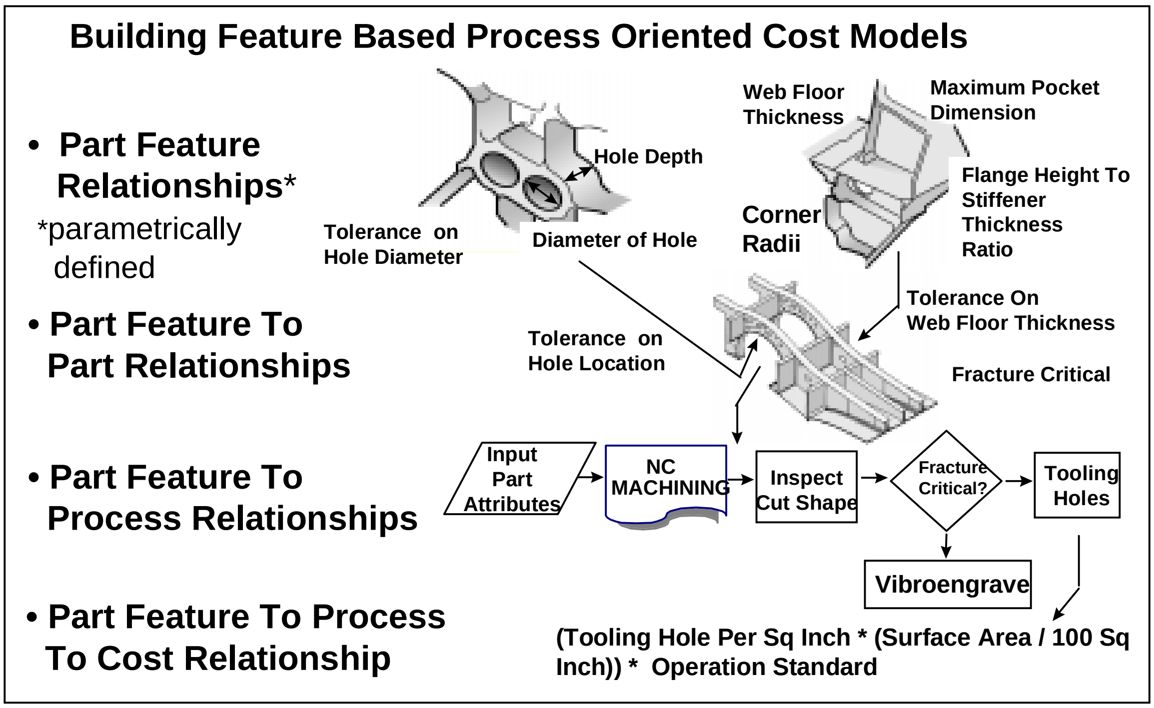


Figure 3-8. Feature and Process Relationships for Machining

3.6 Commercialization

A key requirement for the SAVE program is to have a commercialization plan for utilizing the technology developed on the program. Cognition Corporation is currently enhancing and integrating the CostLink into their product line. They will also use the cost models generated under this program.

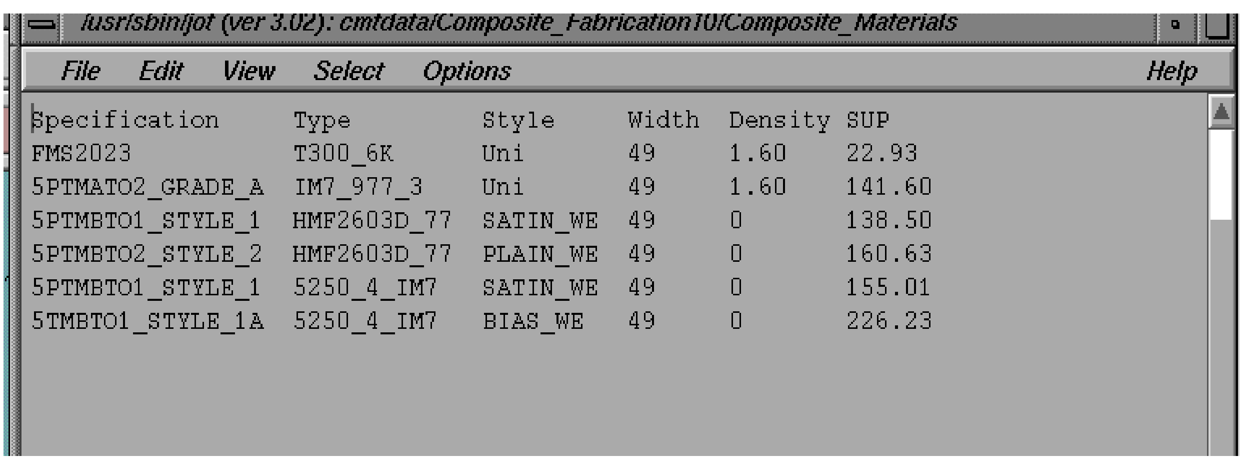
4.0 SAVE Developed Knowledge Bases

Four cost models were developed under the SAVE program: sheet metal, assembly, machining, and hand lay-up composites. The intent of these models was to demonstrate utilizing simulation data available through the SAVE tools to improve cost estimating accuracy and reliability. The following section describes the underlying cost estimating shell tool used, model descriptions and capabilities, feature based costing description, and typical data elements. Additional detail is available in the Cost Model User's Guide, Appendix J.

The SAVE cost models are built using Cognition Corporation's Cost Advantage™. The product is a Design for Manufacturing (DFM) expert system shell. It is a knowledge-based software system that provides expert-level design guidance and analyzes manufacturing alternatives and producibility, returning a predictive cost analysis. In essence, it captures manufacturing process knowledge and uses that information to identify cost drivers. It supports evaluation of a design based on features, materials, and processes. The tool assigns costs to these attributes and provides a total cost estimate of a part or assembly. While SAVE is only calculating cost based on manufacturing constraints, Cost Advantage™ may be used for developing costs for other phases of the life cycle. Cost Advantage™ runs on several Unix-based operating systems, as well as on a PC with the NT operating system.

4.1 Knowledge Base Approaches in Phase I and Phase II

During Phase I, cost models for machining and hand lay-up manufacturing processes were developed. Information required to drive these cost models was obtained from the CAD link, which provided information on product features that drive the knowledge bases. The features were either automatically identified by the software or were annotated using the CAD annotator software. The knowledge bases were developed as generic models using algorithms that are applicable to any machining or composites shop. The company specific and or proprietary data is stored in a set of external tables. An example of these tables is shown in Figure 3-9. When other companies implement these models, the tables will need to be populated with their specific information.



Specification	Type	Style	Width	Density	SUP
FMS2023	T300_6K	Uni	49	1.60	22.93
5PTMATO2_GRADE_A	IM7_977_3	Uni	49	1.60	141.60
5PTMBTO1_STYLE_1	HMF2603D_77	SATIN_WE	49	0	138.50
5PTMBTO2_STYLE_2	HMF2603D_77	PLAIN_WE	49	0	160.63
5PTMBTO1_STYLE_1	5250_4_IM7	SATIN_WE	49	0	155.01
5TMBTO1_STYLE_1A	5250_4_IM7	BIAS_WE	49	0	226.23

Figure 3-9. External Table Example for Company Proprietary Data

During the final phases of the program, cost models for sheet metal and assembly manufacturing processes were developed. Lessons learned from the first two models were applied. Some additional approaches were included to provide future users with alternative ways to create a cost model. Some of these enhancements include: Alternative views, option for manual engineering data entry for companies not fully integrated with CAD, learning curve alternatives, embedded cost estimating relationships. Additional capabilities for utilizing SAVE and CAD data in the cost models were also included in these phases. As in the first phase, the capability to easily extend the cost estimating models to reflect a company's business and manufacturing environment was maintained.

4.2 Typical Data Elements in a Cost Model

The SAVE cost estimating tool provides the capability to input and output many types if information. Figure 3-10 describes typical types of data that are included in the cost models. Learning curve formulas, inflation factors, and methods for building up the product cost are built into the SAVE models. These can be customized to reflect a company's particular business environment. Additional types of cost breakdowns can easily be added to the model to support the decision making process. Tables for labor rates, burden factors, and material costs have been developed externally to Cost Advantage™, allowing for easy updates and customization. This also allows a company to maintain its proprietary rates external to the estimating model.

Cost Inputs	Cost Outputs
Feature Parameters	Recurring Manufacturing Labor Cost
Material Type	Recurring Material Cost
Process Selection	Non-recurring Tool Cost
Number or Units	Non-recurring Engineering Cost
Units per Aircraft	First Unit Cost
Weight	Tooling Cost
Programmatics	Quality Assurance Cost
Other	Process Plan Simulation

Figure 3-10. Typical Cost Model Data

The cost estimating models utilized part families to categorize and access cost estimating relationships. The cost families can be customized to reflect different product structures. Some alternative ways to group the estimating relationships are by part size, complexity, or group technology codes.

Producibility guidance is also contained with-in the cost models and comes in many forms with-in Cost Advantage™. Examples include:

- Producibility rules coded into the model.
- Pointers to existing design handbooks.
- Process Capabilities such as Cp,CpK are utilized as cost factors.
- Bounds for the cost are defined.

Figure 3-11 illustrates an example of a producibility rule that is stored in the machining knowledge base.

The following cost estimating models were developed for the SAVE program. Their capabilities and brief descriptions follow. These models are available through the Cognition Corporation and provide a useful starting point for developing similar cost models. Additional descriptions for customizing these models are included in the SAVE Cost Model Development Guide, SAVE Software Product End Item Report, Chapter 6.

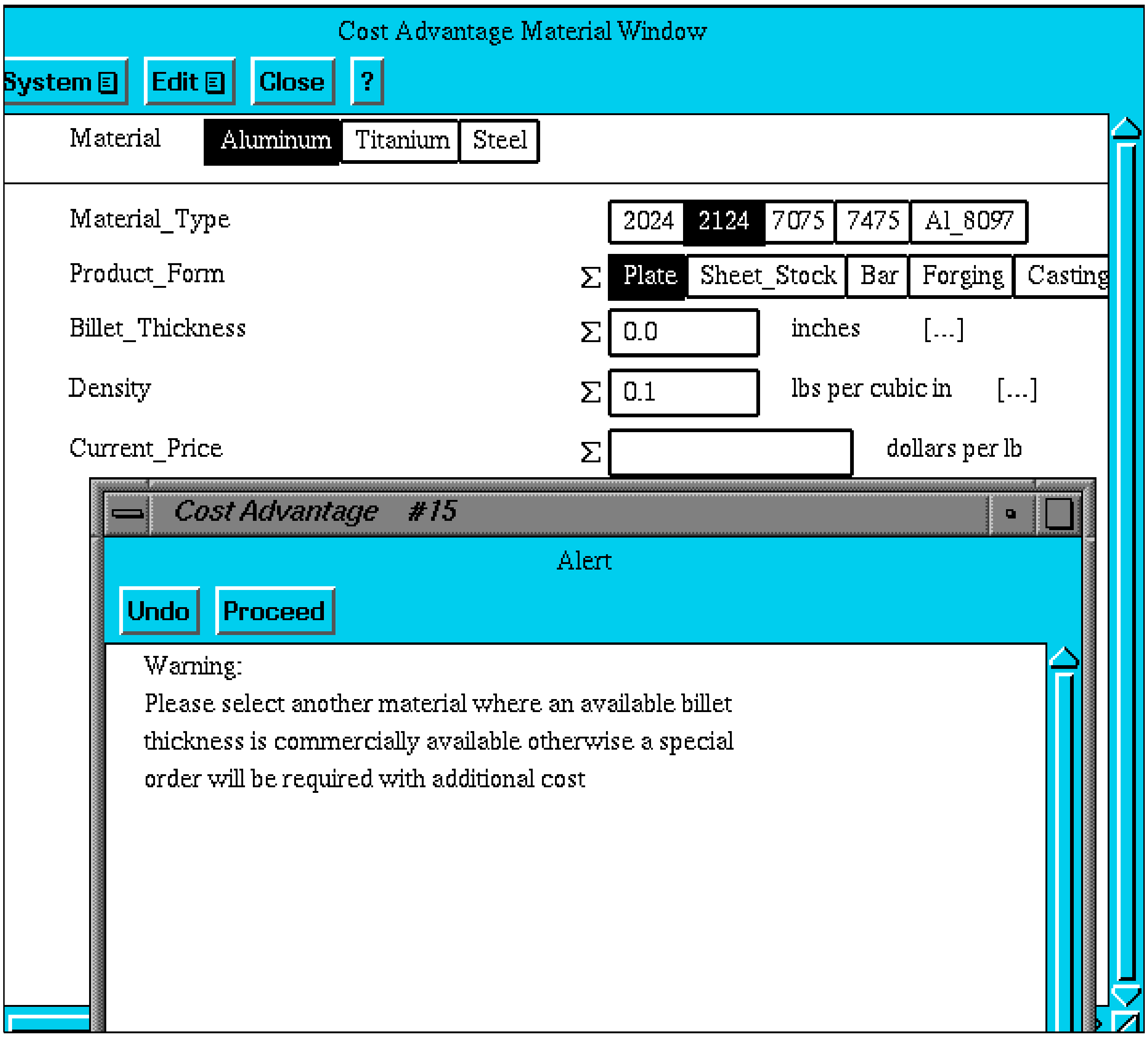


Figure 3-11. Example Machined Knowledge Base Producibility Rule

4.3 Machined Parts

The machining and hand lay-up composite cost models were developed with the same design philosophy. They were designed to provide the capability to add additional part families as well as additional manufacturing operations, cost estimating relationships, and design features. Like the sheet metal cost model described in a future section, the models are designed around families of parts and their associations to manufacturing processes and design features. Costs are calculated using data from the SAVE system, design data from the CAD model though CostLink, and user inputs from within Cost Advantage™. Additional manufacturing operations and design features with their associated cost estimating relationships can be added by the Cost Advantage™ developer. Design features reside in the CA Feature section, and manufacturing operations in the CA Process area. Cost Estimating relationships are calculated in external spreadsheets, placed in an ASCII file, and accessed based on rules and equations in the Cost Advantage™ models. To customize these models, the ASCII files may be updated with values that reflect the facility operations.

A detailed list of the inputs and outputs from this cost model is available in the technical documentation, as well as from the model itself. A 5 tier learning curve was included in the machining and composites model. It is an external C function which was compiled on the Silicon Graphics computer for the first demonstration environment. The machining knowledge base applies to all 5-axis aluminum machined components. Again, due to the flexibility of the Cost Advantage™ tool, these can easily be extended for other materials and processes. Additional summary cost categories can also be included by future developers.

Figure 3-12 is an example of a machined part with design features included in the cost model.

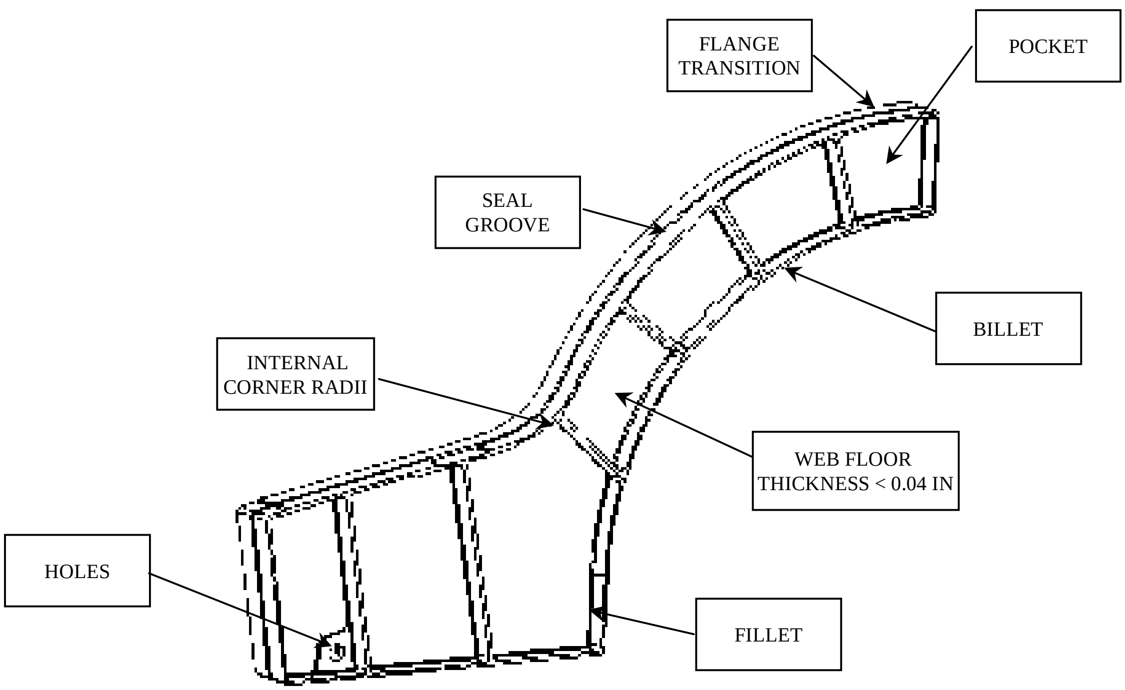


Figure 3-12. Sample Machining Features

4.4 Hand Lay-up Composites Parts

The hand lay-up composite and machining cost models were developed with the same design philosophy. The description from Section 4.3 also applies here. The composite hand laid up knowledge base applies to non-integrally stiffened components laid up on a mold. Figure 3-13 illustrates an example of a hand-laid-up composites producibility rule and input data required to drive the knowledge base.

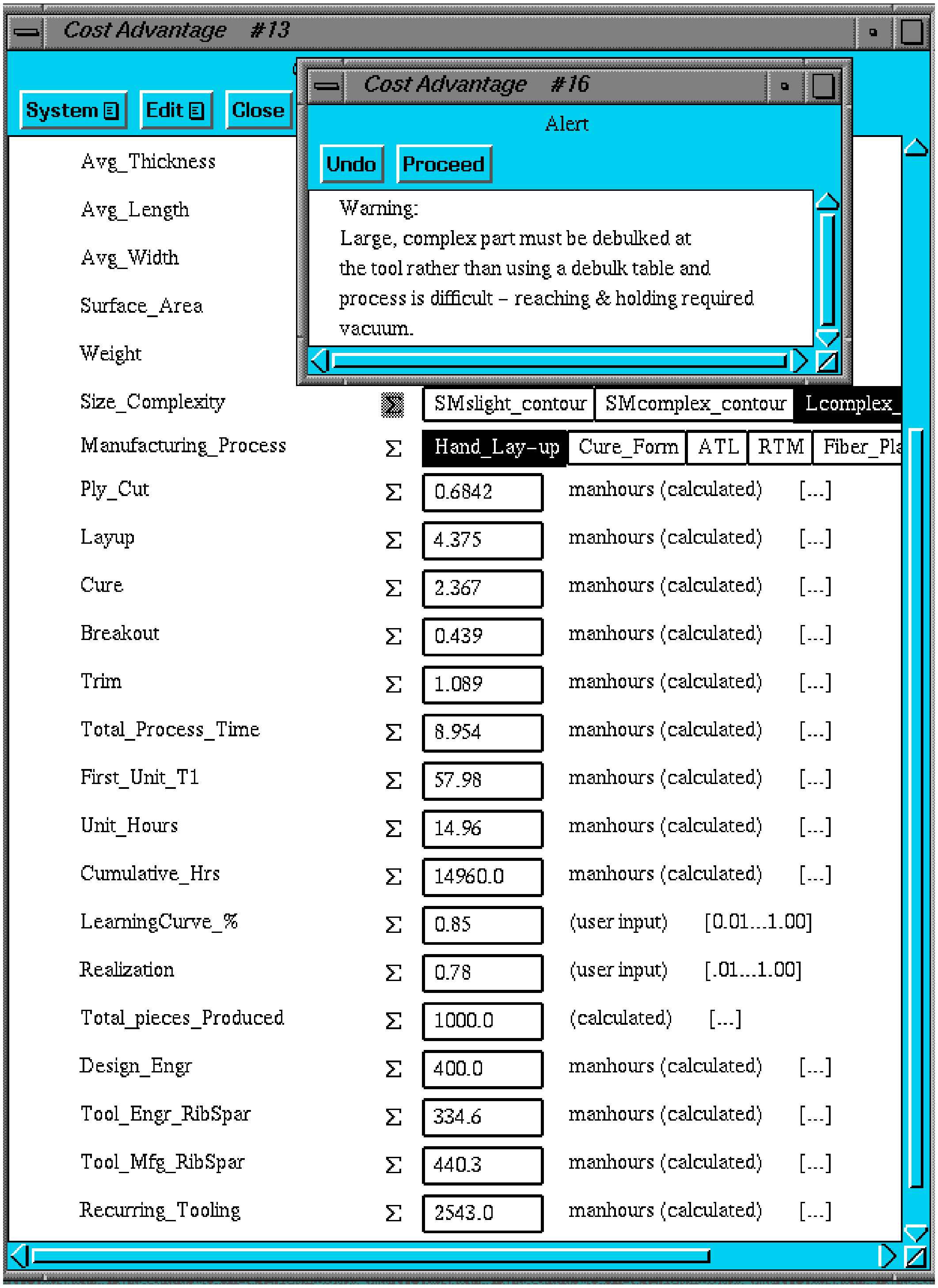


Figure 3-13. Example Hand-Laid-Up Composite Producibility Rule

Figure 3-14 illustrates a composite part with design features included in the hand lay-up composites cost model. Numbers of plies and material type and form are also cost related features.

4.5 Sheet Metal Cost Model Description and Capabilities

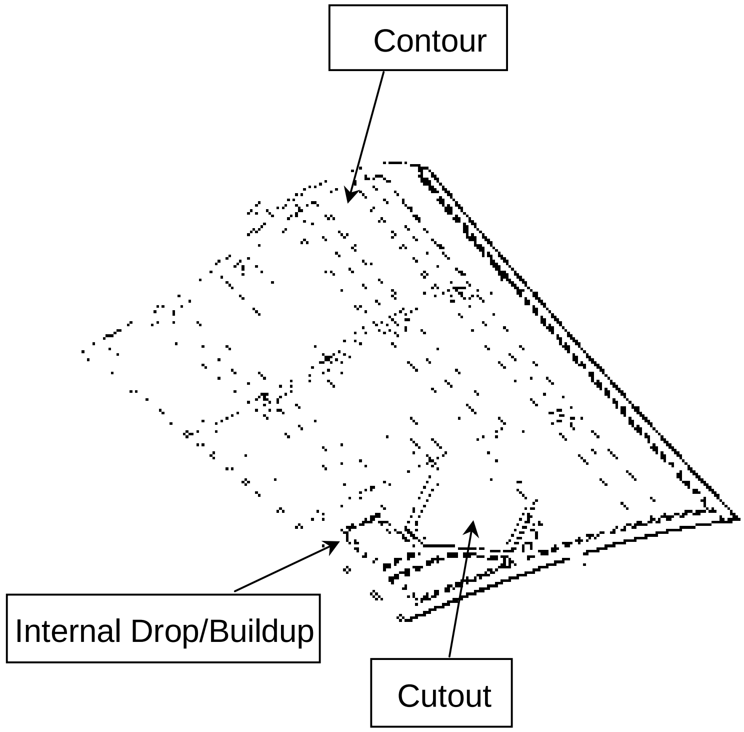


Figure 3-14. Sample Composite Part Characteristics

As discussed in previous sections, the Sheet Metal cost model is designed around families of parts and their associations to manufacturing processes and design features. A cost is calculated using data from the SAVE system, design data from CostLink, and user inputs from within Cost Advantage™. Additional manufacturing operations and design features with their associated cost estimating relationships can be added by the Cost Advantage™ developer. Component cost models such as the sheet metal, machining, and composites models have the design features residing in the CA Feature section, and manufacturing operations in the CA Process area.

Manufacturing Operations Currently in the Sheet Metal Cost Model include:

Layout	Shear	Drill
Rout	Hydroform	Corrosion Protection
Heat Treat	Fluid Cell or Hydraulic Press	Inspect
Mark	Age Harden	Trim
Mask	Sand	Deburr
Straighten	Clean	

The model is designed to provide the capability to add additional part families as well as additional manufacturing operations, cost estimating relationships, and design features. Unique functionality demonstrated in this model includes:

- Process Plan from SAVE dB
    - A toggle used when a process plan is available from the SAVE manufacturing simulations. If the toggle is off (i.e., there is no plan from SAVE), a template within Cost Advantage™ is used.

- Fabrication Site
  - This variable can be used to specify company locations as well as vendor sites. Use these to customize access into rate tables or to modify cost estimating relationships to reflect the capabilities of a specific site or vendor.

Figure 3-15 illustrates a sheet metal part with features included in the cost model. Additional contour and other forming features are in the models. Material Type, Density, Initial and final material conditions are also important cost driving features in the model.

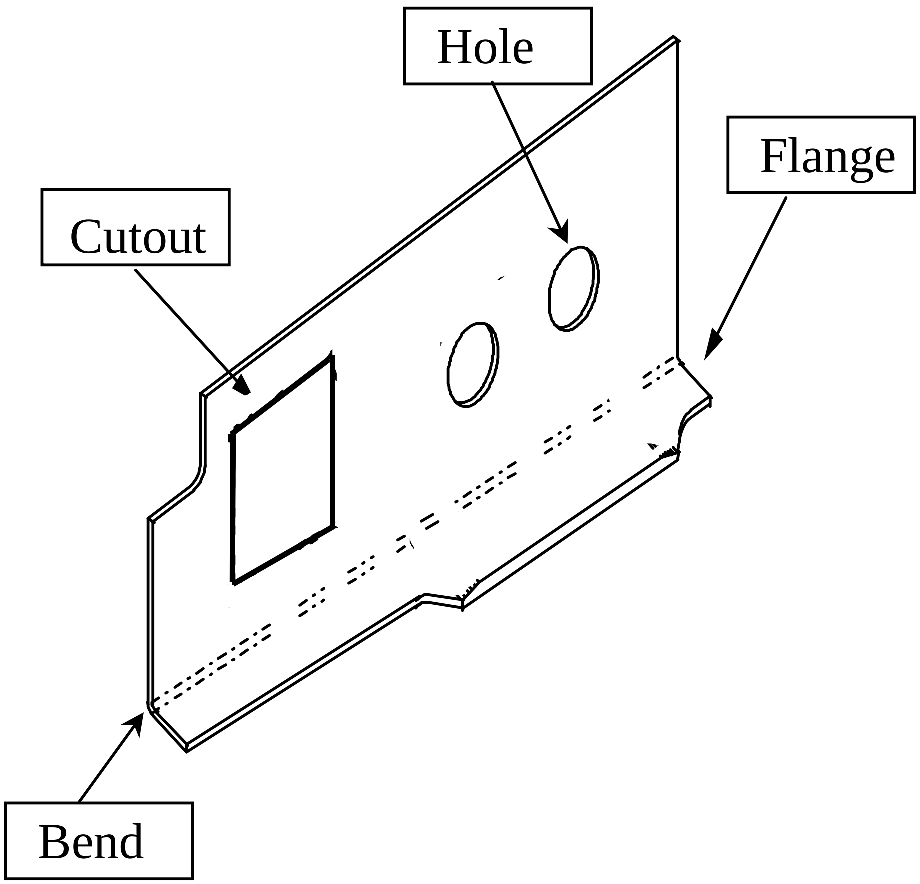


Figure 3-15. Sample Sheet Metal Design Features

4.6 Assembly Cost Model Description and Capabilities

The assembly cost model is designed around assembly oriented manufacturing operations. These are stored in Cost Advantage™ as CA Features. A cost is calculated using data from the SAVE system, such as the process plan and business data; design data from CostLink; and user inputs from within Cost Advantage™. Additional manufacturing operations and design features with their associated cost estimating relationships can be added by the Cost Advantage™ model developer. Figure 3-16 shows an example of a Phase I Assembly Cost Report Based on Bill of Material roll-up. Cost roll-ups can occur in either Cost Advantage™, or an external system.

Cost Advantage Summary Window: HorizStab

System | Edit | Viewing | CDF | Open | Close | ?

	ULDDRLFX	1	25.560	0.000		25.560
	MVTOSKNA	1	9.711	0.000		9.711
	REAMCNSK	1	434.100	0.000		434.100
	DEBURR	1	358.600	0.000		358.600
	INSTFAST	1	2242.000	0.000		2242.000
	MVTOLE	1	9.711	0.000		9.711
	LOADASSY	1	193.600	0.000		193.600
	INSTNUTP	1	424.100	0.000		424.100
	INSTBOLT	1	283.100	0.000		283.100
	INSTNAME	1	277.900			277.900
	MVTOINSP	1	9.711	0.000		9.711
	REMVPLY	1	202.600	0.000		202.600
	INSPECT	1	762.000	0.000		762.000
	Parts					
»	16T7462A91S	1	2046.000	3498.000	1726.000	7269.000
»	16T7469-9S	1	564.900	205.200	601.500	1372.000
»	16T7475-19S	1	223.400	1.560	34.190	259.200
»	16T7466-9S	1	208.600	146.600	317.400	672.600
»	16T7474-7S	1	360.600	48.320	460.900	869.800
»	16T7482-13S	1	229.200	17.330	407.500	654.100
»	16T7482-911S	1	229.200	17.330	407.500	654.100
»	16T7476-11S	1	0.000	28.100	0.000	28.100
»	16T7476-7S	1	0.000	5.500	0.000	5.500
»	16T7476-7S	1	0.000	5.500	0.000	5.500
»	16T7476-9S	1	0.000	48.000	0.000	48.000
»	16T7475-39P	1	0.000	30.930	0.000	30.930
»	16T7475-43	1	0.000	10.330	0.000	10.330
»	16T7483-9	1	0.000	325.000	0.000	325.000
»	16T7463-5S	1	4973.000	1603.000	3852.000	10430.000
»	16T7465-3S	1	1916.000	1637.000	615.100	4168.000
»	16T7465-4S	1	1916.000	1637.000	615.100	4168.000

Figure 3-16. Example of Phase I Assembly Cost Report Based on Bill of Material Roll-up

Phase II provided the opportunity to apply lessons learned to the initial assembly knowledge base. Manufacturing operations were streamlined to reflect common assembly processes. In Phase I, two discrete models were utilized—one calculating dollars, and one calculating hours. To increase the robustness of the tool as well as maintainability of the model, a new knowledge base was created that integrated the best features of both models. Capabilities were developed to import both manufacturing process information from the SAVE database, plus labor hours that result from the manufacturing simulations run in other tools. This provides an ability to more accurately represent the cost of the assembly based on our simulations, not just pre-defined standards. Figure 3-17 shows a Phase II demonstration screen ready to accept simulation data from other SAVE tools.

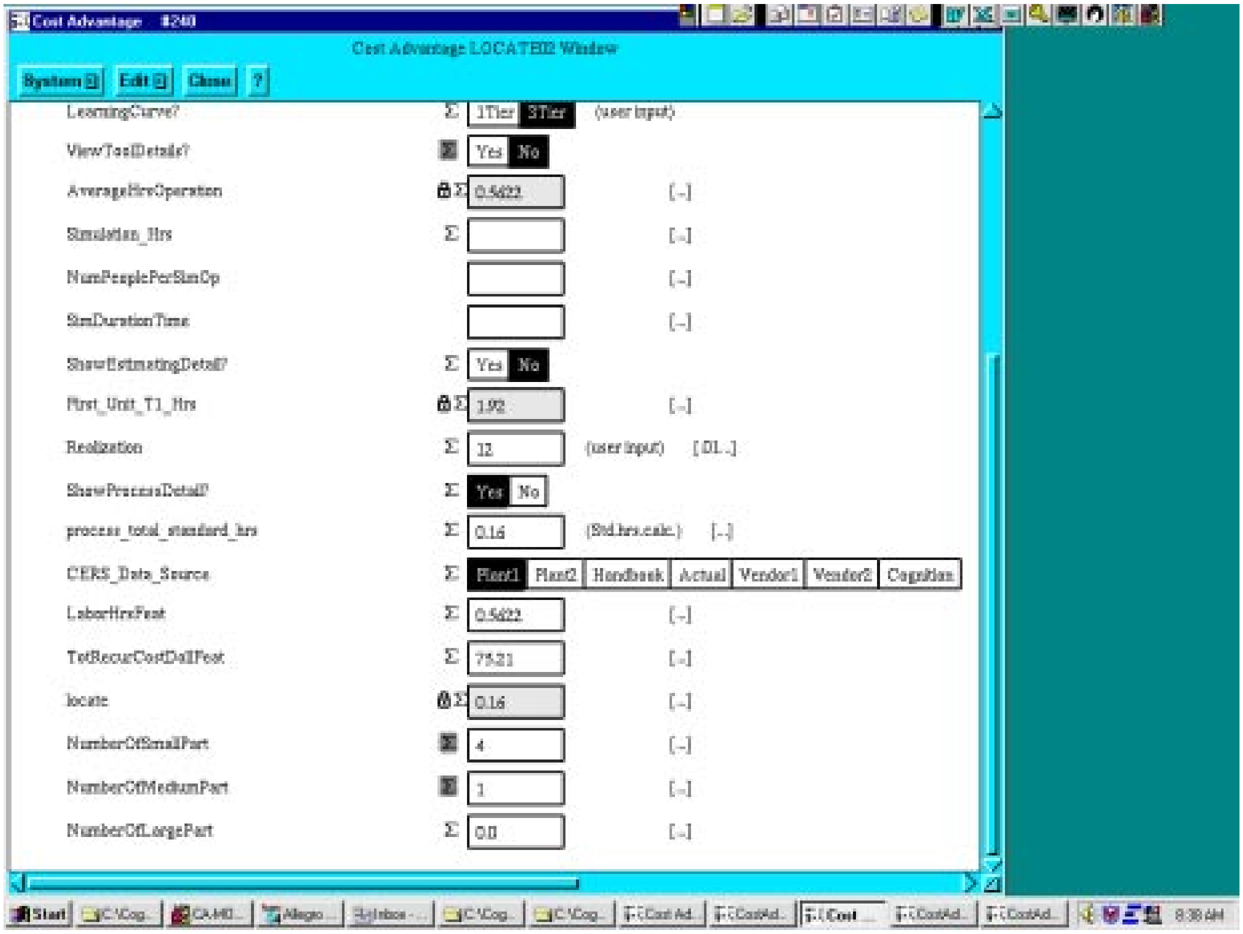


Figure 3-17. Phase II Demonstration CA Screen Ready for Simulation Inputs

The Figure 3-18 Assembly knowledge base screen shot reflects the inputs and outputs at the part level of the assembly. Numbers of parts are calculated based on data received from CATIA™ via the CostLink.

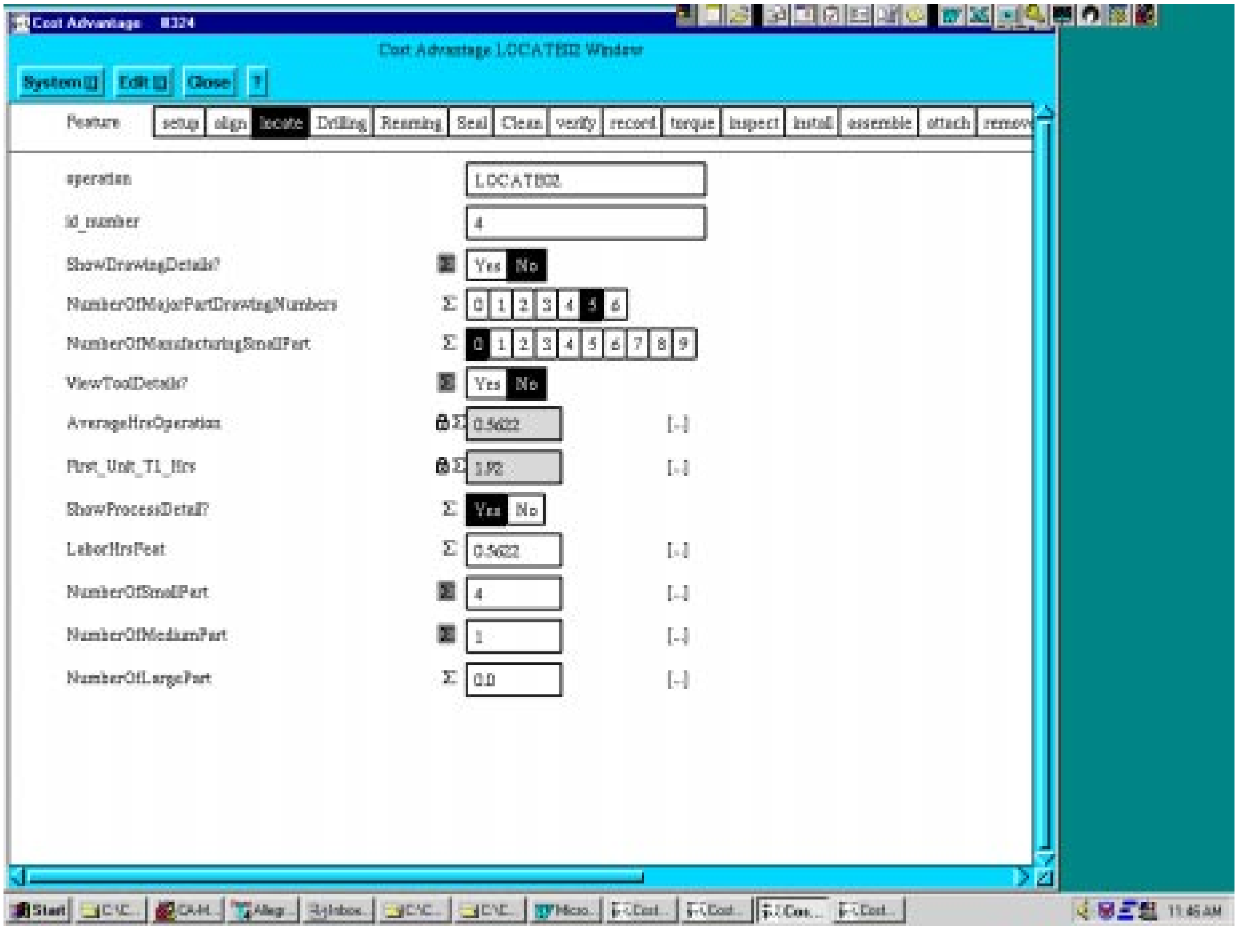


Figure 3-18. Example of Detailed Feature Input Screen

Figure 3-19 lists the assembly operations included in the Phase II assembly cost model. Algorithms and cost estimating relationships can be easily edited to represent the current practices at the company.

Setup	Align	Locate
Drill / Drill Ream	Resistance Spot weld	Back Drill
Bench Drill	Spot Face	Drill Out
Ream	Finish Ream	Seal
Verify	Record	Torque
Inspect	Install	Assemble
Attach	Remove	Shim
Cold Work	Packing	Bond Check
Deburr	Apply	Rivet

Figure 3-19. Phase II Assembly Knowledge Base Processes

The assembly cost models were developed to accommodate multi-level indented process plans. Each assembly operation listed above can be imported as a Cost Advantage™ feature. Figure

3-20 is a top-level cost estimate summary window. Figure 3-21 is a screen shot from the final demonstration illustrating the capability for layered process plans.

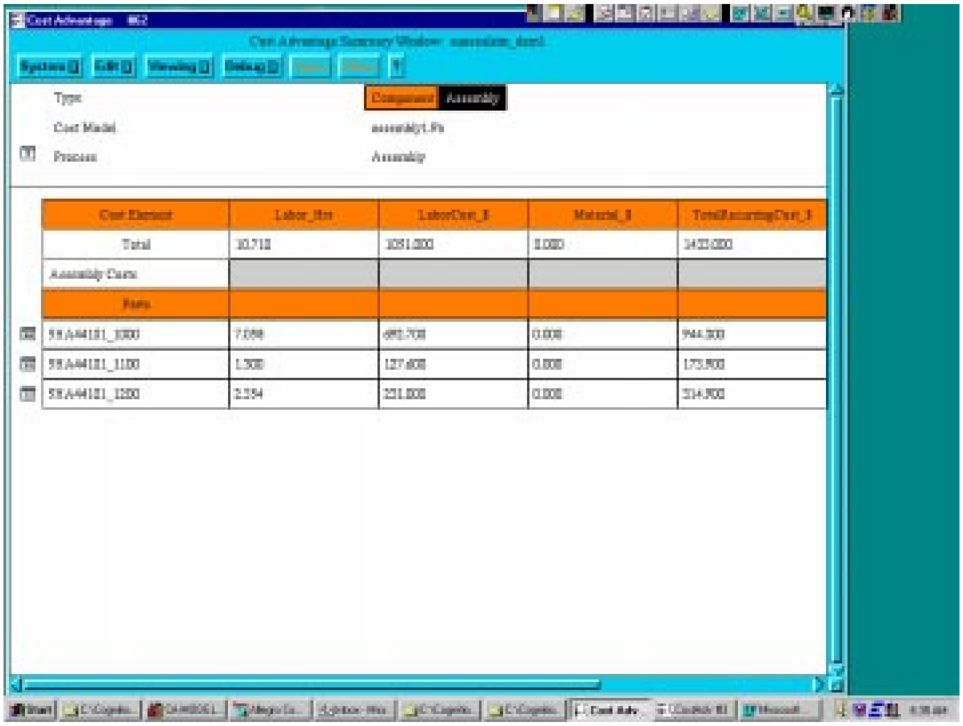


Figure 3-20. Layered Assembly Process Plan Capability

Figure 3-21. Phase II Demonstration Screen for Layered Assembly Process Steps

5.0 CAD to Cost Model – Cost Link Development

The enhanced design/cost integration task creates a tightly coupled, product-dependent, link between the Cost Modeling system (Cost Advantage™) and the CAD system (CATIA™). This tight coupling is required for when the designer generates product definition data in CATIA™ and the cost and producibility of the product can be rapidly estimated. This is accomplished simply by providing key information about the product to the cost modeling system. The CAD link, CostLink, is the mechanism for providing this information about products to the cost modeling system. The CostLink automatically extracts data from the CAD tool and electronically provides this information to the cost estimating tool. The final demonstration showed the capability for extracting part and assembly feature data for the F-22 auxiliary seal door, and utilizing it in the cost model. Figure 3-22 is the CATIA™ model for this door as used in the demonstration.

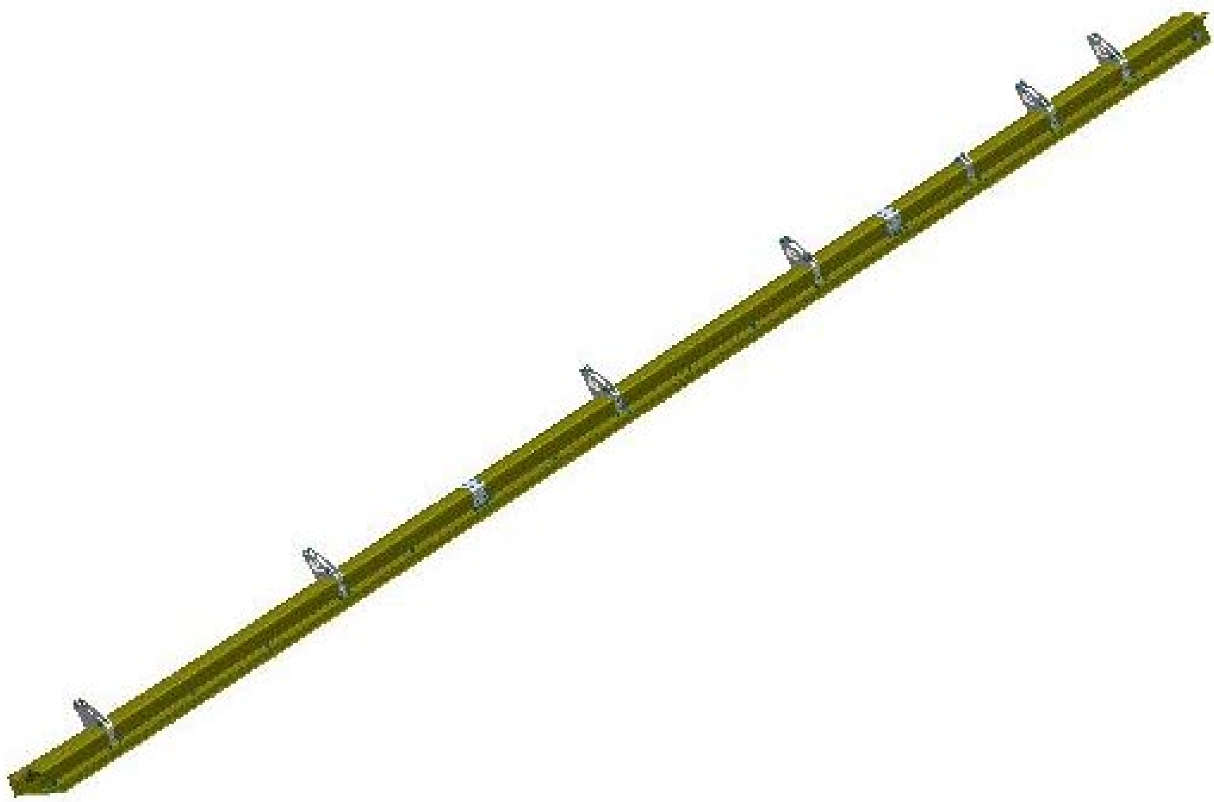


Figure 3-22. Final Demonstration F-22 Auxiliary Seal Door Demonstration Assembly

Details of the initial approaches to cost design integration and the initial version of CostLink are detailed in the prior interim reports. These include development of a specialized cost link dependent on specific features, and an annotator. This annotator provided the designer the capability to define cost features in their CATIA™ model for transfer of data into the cost model. This was required because some features could not be automatically identified. Therefore, a means of manually annotating the CAD database with information was necessary to drive the cost modeling system.

Figure 3-23 shows a sample session from Phase I for a machined rib. This Phase I system was capable of handling a limited number of features for simple one-sided, 5-axis machined parts and non-integrally stiffened hand-laid-up composites.

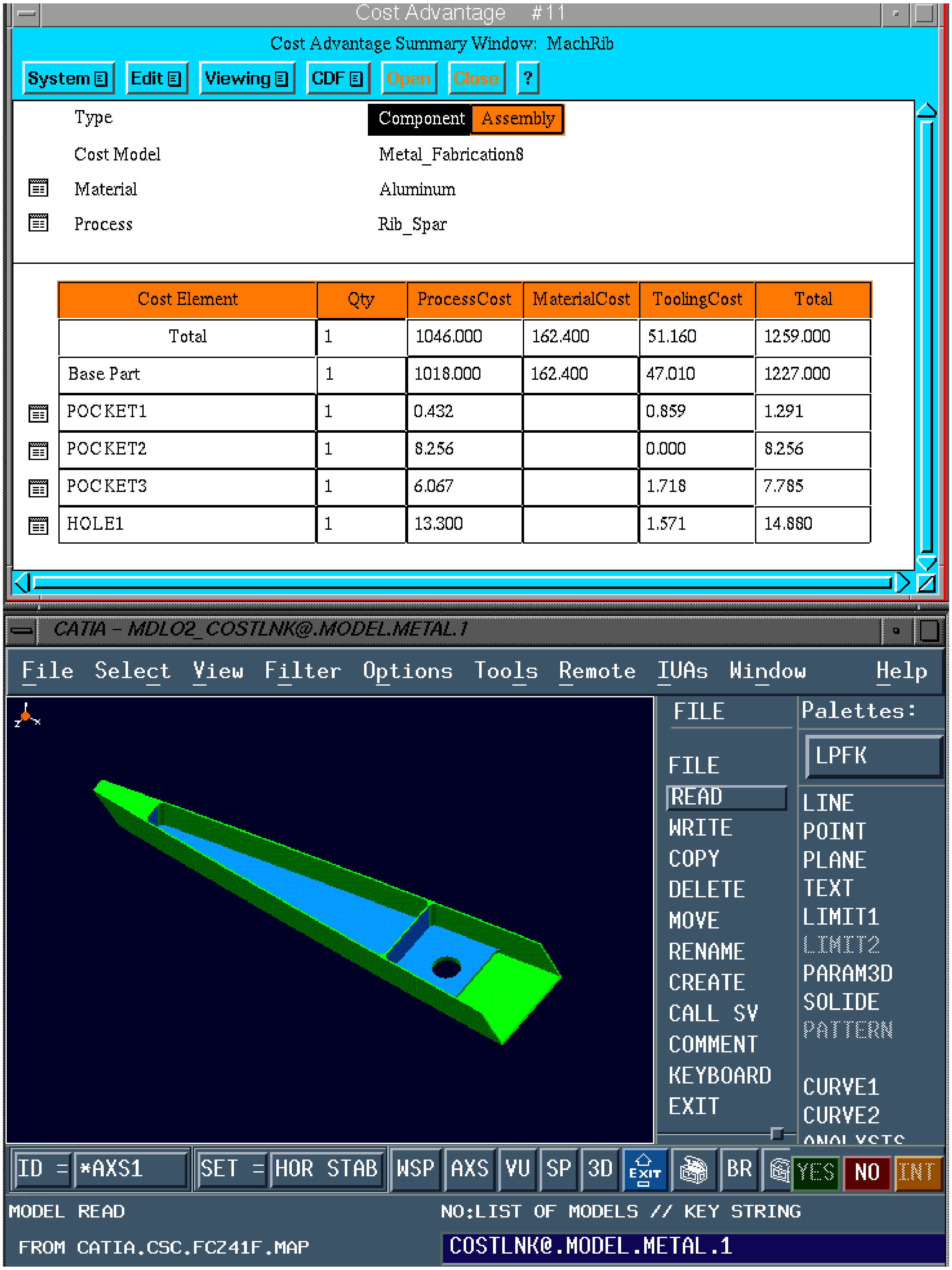


Figure 3-23. Phase I Demonstration For a Machined Rib

The final approach for the CostLink reflects lessons learned from the earlier implementations. The Phase II CostLink implementation is described here and in the final Software User's Manual, Appendix I – CATIA™ CostLink User's Guide. A more detailed description of the current CostLink capabilities and future enhancements may be found in the Cognition Corporation product specification. The Phase II version of the CostLink was designed to utilize the basic CATIA™ capability and a company's "Best Practices." The system supports both individual components and assemblies as shown in Figure 3-24. This more general approach will acquire CATIA™ feature information as well as assembly session data. This provides a more robust capability which will be integrated into the commercial product.

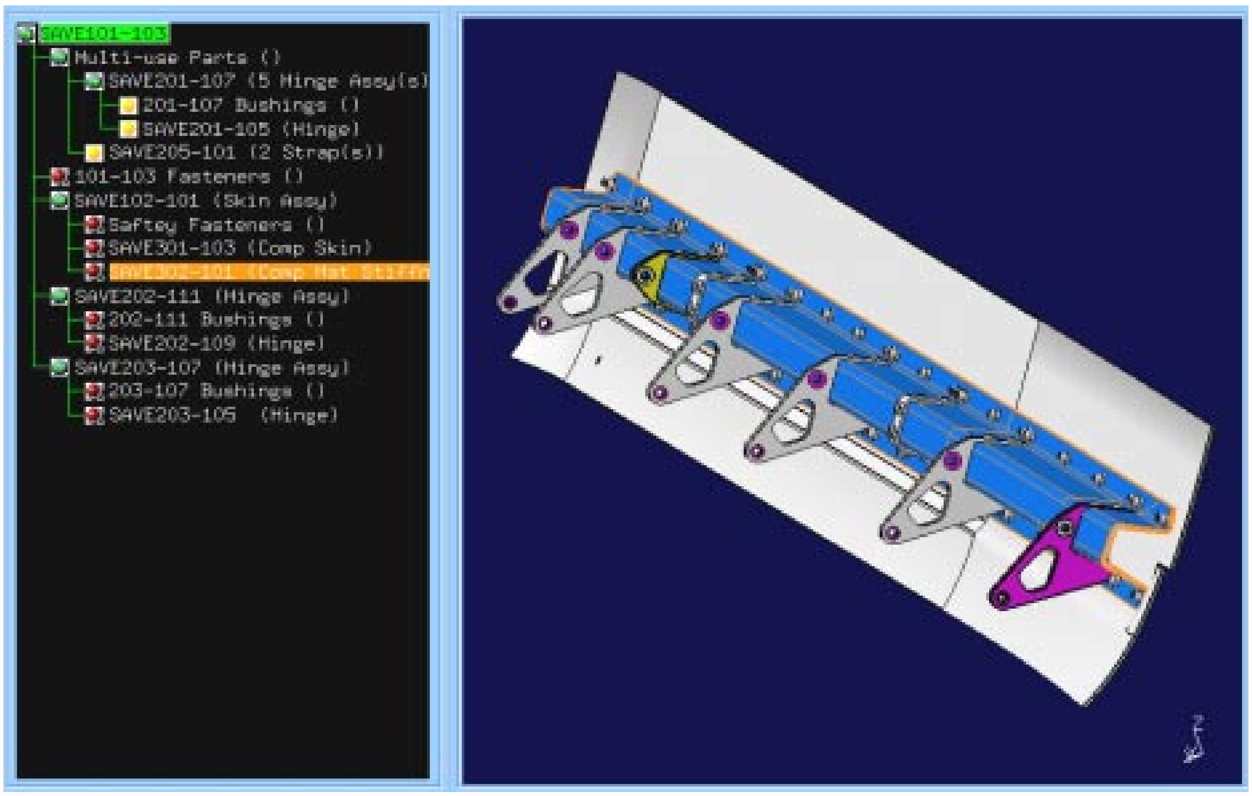


Figure 3-24. SAVE Door Assembly CAD Data Example

The Assembly CostLink is currently developed for CATIA™ version 4.1.9 on the IBM AIX platform. A new revision of CostLink for a future version of CATIA™ is currently being developed by Cognition for commercialization, based on lessons learned from the SAVE program. Cognition has developed an object-based schema for CAD data similar to the SAVE schema. This provides additional functionality for future uses of CAD data.

Chapter 4

Phase I Initial Demonstration

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 Objective of Phase I Demonstration

The objective of the SAVE Phase I demonstration was to validate that an integrated suite of simulation, modeling and analysis tools could produce results that closely correlate to manufacturing actuals from a real-world fighter production program. The component selected for this validation was the F-16 Horizontal Stabilizer. This component was selected for three reasons:

(1) The stabilizer structural configuration was dramatically changed during the early phases of the F-16 LRIP program due to performance factors;

(2) The change made to the stabilizer was isolated from most other manufacturing activities so the data collected from the historic files could be easily isolated for direct correlation to the simulated data; and

(3) The F-16 program provided an extensive database that could be used to analyze the simulation results.

The Phase I demonstration showed how integrated tools could be used to perform modification trades based on cost, risk and schedule.

The specific goals of the Phase I demonstration were:

(1) validation of the tool set concept of operations;

(2) integration of the tool set; and

(3) showing that the validated, integrated tool set could produce a real-world savings.

Validation of the tool set consisted of comparing simulation results to real-world actuals. The results ranged from 3% to 18% variation. With one element, cost, consistently producing a 15% difference between simulated results and actual results. This indicates a discrepancy in the knowledge bases that can be located and corrected. Table 4-1 summarizes the results.

Table 4-1. Comparison of Simulated Results Versus Actuals

METRIC	DEVIATION BETWEEN SIMULATION AND ACTUALS
Cost	15%
Schedule	18%
Risk	3%

The integration of the tool set included the application of new infrastructure techniques and technologies. The tools were encapsulated so they could be executed from a common desktop environment. TCP/IP and NFS were used so a distributed, heterogeneous environment could be implemented. Seven tools were implemented in this environment and the application of existing and SAVE developed import/export capabilities were used. Data were then tested through each of the interfaces.

With regard to demonstration of real-world savings, the application of the SAVE process was able to produce a cost savings of $113,862 on the remaining F-16 program by identifying the advantage of modifying a skin trim step in the assembly process. Additionally, in addressing the Lean Enterprise metrics, the following accomplishments aided in achieving the SAVE targeted goals:

(1) Design-to-Cost Data Accuracy – End of program target per component is 1.2% and the Phase I scenario resulted in 0.13%;

(2) Lead Time Reduction – End of program target per component is 48 hours from component span and the Phase I scenario resulted in a 3.8 hour reduction from component span;

(3) Design Change Reduction – End of program target per component is 8.8 fewer changes and the Phase I scenario resulted in 23 fewer changes per component; and

(4) Scrap, Rework and Repair Reduction – End of program target per component is 0.44% and the Phase I scenario resulted in 0.1% reduction per component.

The key features of the Phase I demonstration include:

- Integration of seven industry-leading, state-of-the-art, commercial-off-the-shelf tools into the SAVE infrastructure;
- Focus on F-16 assemblies and details;
- Focus on generic manufacturing operations;
- Demonstration that is reflective of real-world E&MD processes progressing from structural concept selection, to assembly process optimization to detail part analysis;
- Demonstration of measurable metrics and how they relate to overall weapons system affordability goals.

2.0 Phase I Tools

The Phase I core tools included the following categories: CAD, Cost Modeling, Assembly Simulation, Factory Simulation, Work Instructions, Risk Assessment, Schedule Simulation and Manufacturing Capabilities risk assessment. To demonstrate these classes of tools, the COTS products listed in Table 4-2, were used.

Table 4-2. Phase I Tools and Vendors

TOOL CATEGORY	TOOL VENDOR	TOOL NAME
CAD	IBM/Dassault	CATIA
Cost Modeling	Cognition Corporation	Cost Advantage
Assembly Simulation	Deneb Robotics	IGRIP/ERGO
Factory Simulation	Deneb Robotics	Quest
Work Instructions	Deneb Robotics	IGRIP/ERGO

Table 4-2. Phase I Tools and Vendors (Continued)

Risk Assessment	SAIC	ASURE
Schedule Simulation	Symix	FACTOR/AIM
Production Cost Models	Lockheed Martin	PCM
Manufacturing Capabilities	GRCI	JMCATS

Within each of these tools, one or more models were produced for the purpose of the demonstration. The models were used to conduct the three trade studies—structural concept selection, manufacturing method plans, and detail part concepts—described in Section 3.0. The following sections contain descriptions of how each tool class was used during the demonstration, illustrations of the models, and short narratives describing the models built within the tool.

2.1 CAD

CAD models (shown in Figures 4-1, 4-2 and 4-3) were built to represent each structural concept, and detail models were built for both the machined and composite version of the tip rib.

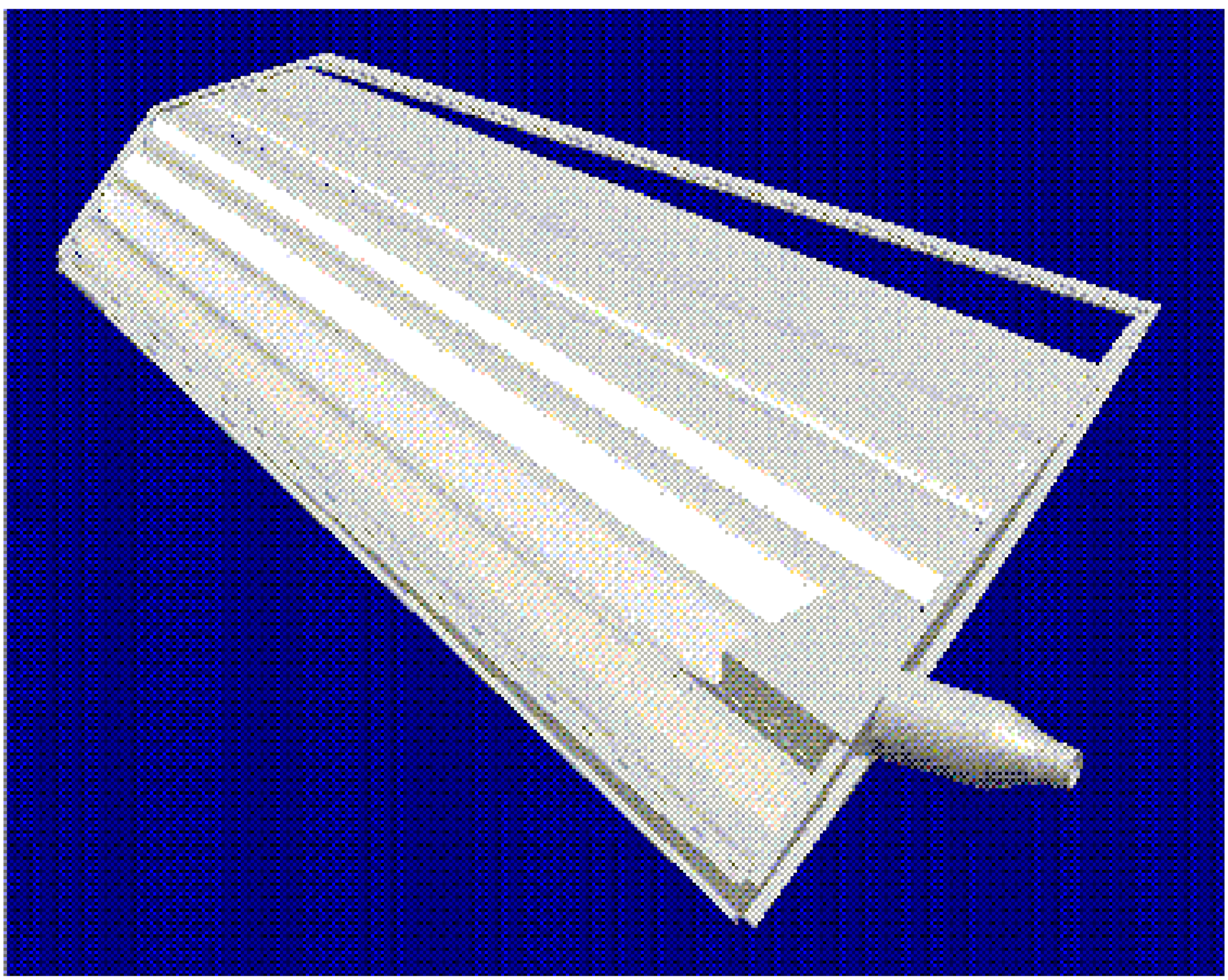


Figure 4-1. CAD Model of Corrugated Structural Configuration

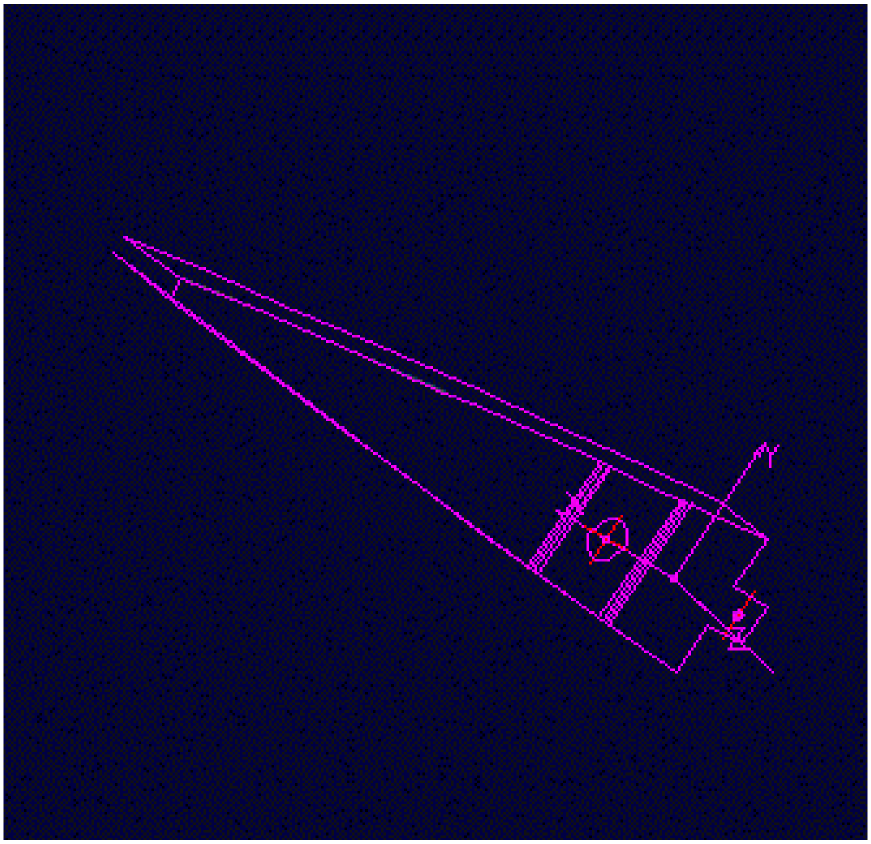


Figure 4-2. CAD Model of Composite Tip Rib

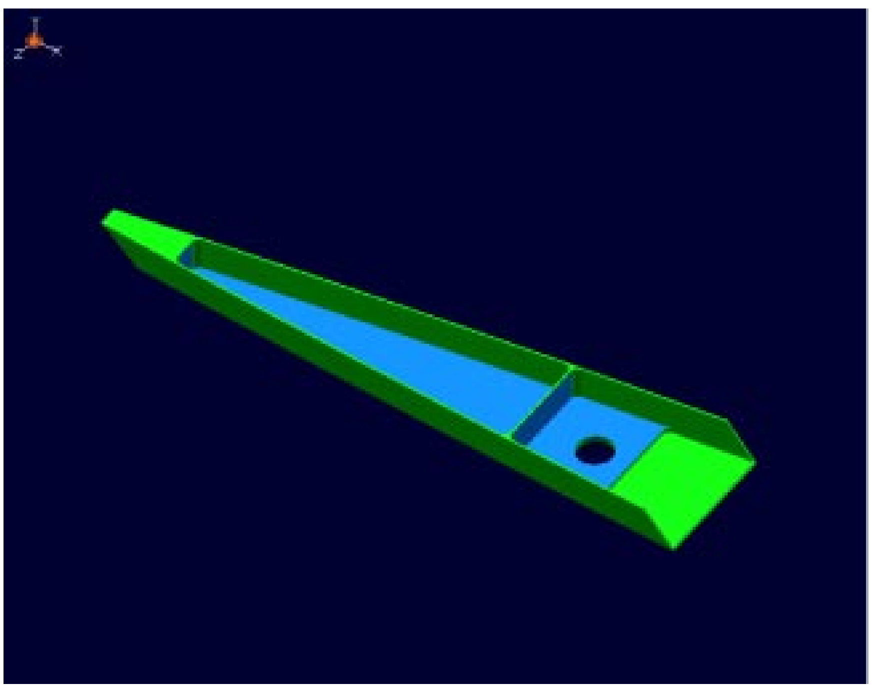


Figure 4-3. CAD Model of Machined Tip Rib

2.2 Cost Modeling

Several cost models or knowledge bases were developed for use during Phase I. These included models for assembly processes, assembly bill of materials, machined parts and hand lay-up composite parts. These models provided the basis for further refinements during Phase II. Figure 4-4 provides an example of the inputs required for one of the knowledge bases.

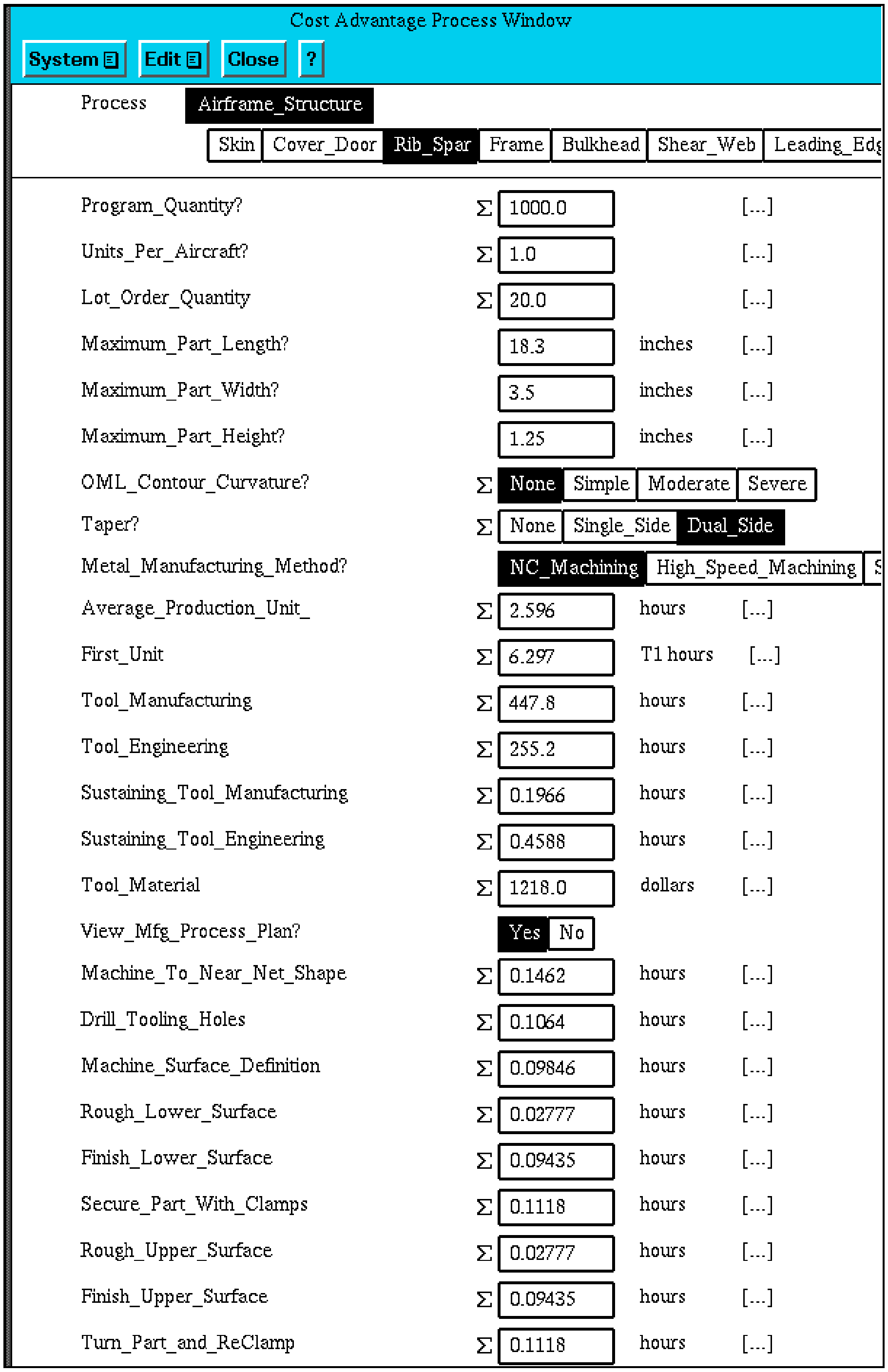


Figure 4-4. Example Knowledge Base Inputs

Figures 4-5 and 4-6 provide example outputs of the Cost Advantage knowledge base for assembly processes. The processes used in this example were obtained electronically from the SAVE CDF generated by Factor/AIM, Quest and IGRIP/ERGO.

Cost Element	Qty	ProcessCost	MaterialCost	ToolingCost	Total
Total	1	37970.000	9304.000	13610.000	60890.000
Assembly Costs	1	0.000	0.000	4249.000	4249.000
SETUP	1	81.060	0.000	0.000	81.060
LOADASFX	1	694.600	0.000	0.000	694.600
ULDPARTS	1	496.600	0.000	0.000	496.600
MILLFAST	1	135.100		0.000	135.100
LOCSKINS	1	352.600	0.000	0.000	352.600
LIQSHIM	1	850.600	0.000	0.000	850.600
LDDRLFX	1	25.100	0.000	0.000	25.100
DRILL	1	1340.000	0.000	0.000	1340.000
ULDDRLFX	1	25.100	0.000	0.000	25.100
DEBURR	1	358.600	0.000	0.000	358.600
INSTFAST	1	2242.000	0.000	0.000	2242.000
LOADASSY	1	202.600	0.000	0.000	202.600
INSTNUTP	1	424.100	0.000	0.000	424.100
INSTBOLT	1	283.100	0.000	0.000	283.100
INSTNAME	1	277.900		0.000	277.900
REMVPLY	1	211.600	0.000	0.000	211.600
INSPECT	1	18290.000	0.000	0.000	18290.000

Figure 4-5. Example Cost Report

Cost Advantage Summary Window: HorizStab

System | Edit | Viewing | CDF | Open | Close | ?

ULDDRLFX	1	25.560	0.000		25.560
MVTOSKNA	1	9.711	0.000		9.711
REAMCNSK	1	434.100	0.000		434.100
DEBURR	1	358.600	0.000		358.600
INSTFAST	1	2242.000	0.000		2242.000
MVTOLE	1	9.711	0.000		9.711
LOADASSY	1	193.600	0.000		193.600
INSTNUTP	1	424.100	0.000		424.100
INSTBOLT	1	283.100	0.000		283.100
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MVTOINSP	1	9.711	0.000		9.711
REMVPLY	1	202.600	0.000		202.600
INSPECT	1	762.000	0.000		762.000
Parts					
16T7462A91S	1	2046.000	3498.000	1726.000	7269.000
16T7469-9S	1	564.900	205.200	601.500	1372.000
16T7475-19S	1	223.400	1.560	34.190	259.200
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16T7474-7S	1	360.600	48.320	460.900	869.800
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16T7482-911S	1	229.200	17.330	407.500	654.100
16T7476-11S	1	0.000	28.100	0.000	28.100
16T7476-7S	1	0.000	5.500	0.000	5.500
16T7476-7S	1	0.000	5.500	0.000	5.500
16T7476-9S	1	0.000	48.000	0.000	48.000
16T7475-39P	1	0.000	30.930	0.000	30.930
16T7475-43	1	0.000	10.330	0.000	10.330
16T7483-9	1	0.000	325.000	0.000	325.000
16T7463-5S	1	4973.000	1603.000	3852.000	10430.000
16T7465-3S	1	1916.000	1637.000	615.100	4168.000
16T7465-4S	1	1916.000	1637.000	615.100	4168.000

Figure 4-6. Example Cost Report Based on Bill of Material Roll Up

Figure 4-7 shows an example of producibility rule that is presented to the user during a Cost Advantage session. The knowledge base can be expanded and customized for each company and process.

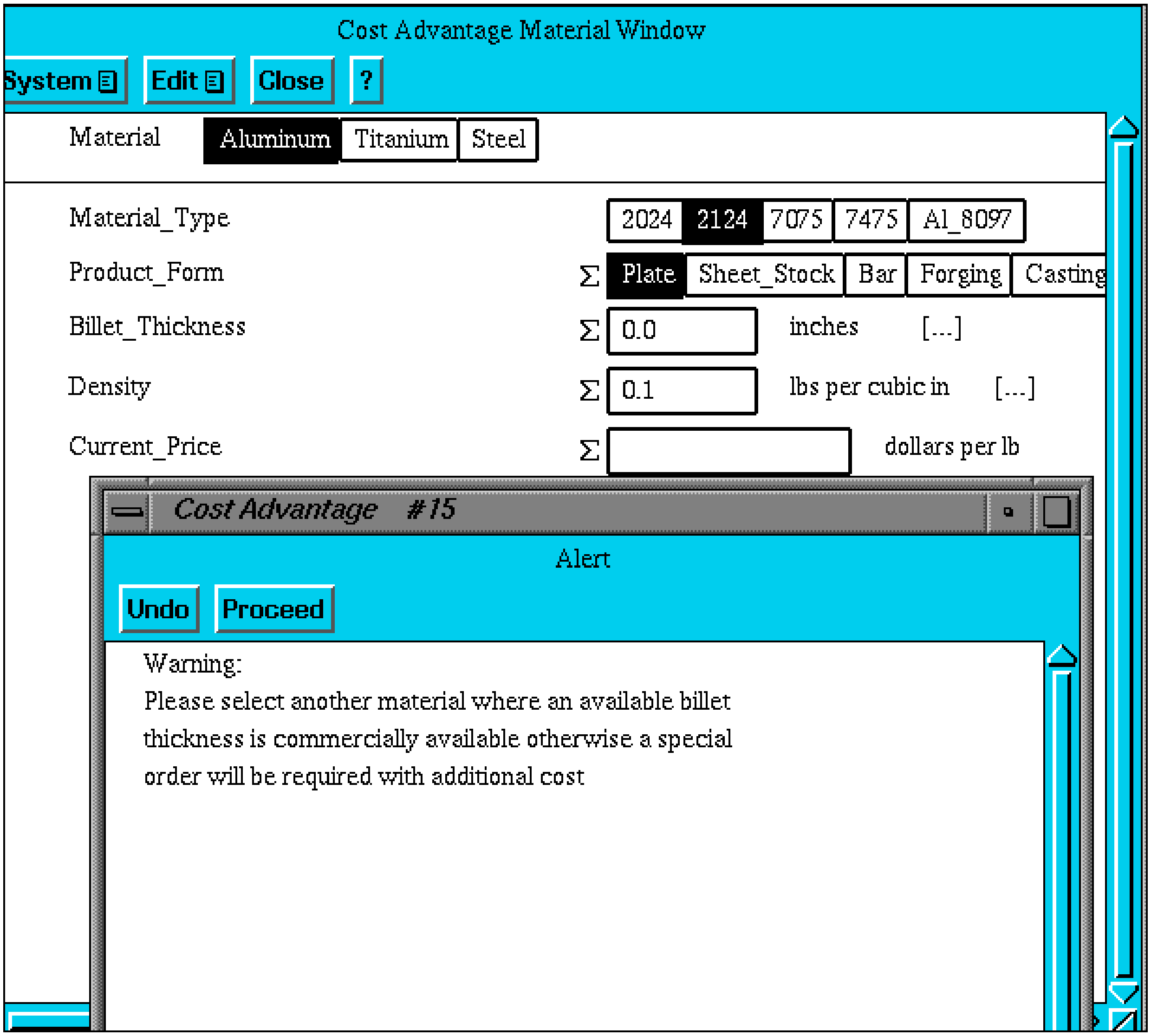


Figure 4-7. Example Producibility Rule from Knowledge Base

2.3 Assembly Simulation

During Phase I of the SAVE program the primary focus was on the ability to simulate, analyze and model assembly processes. Figure 4-8 is an example model for the robotic drilling process.

In addition to studying automated processes, the SAVE tool suite enabled the user to study manual processes (Figure 4-9). However, it should be noted that the time required to gather the data and build the simulation models could be costly in both schedule and dollars. The key is to identify what needs to be modeled to support the overall decision process.

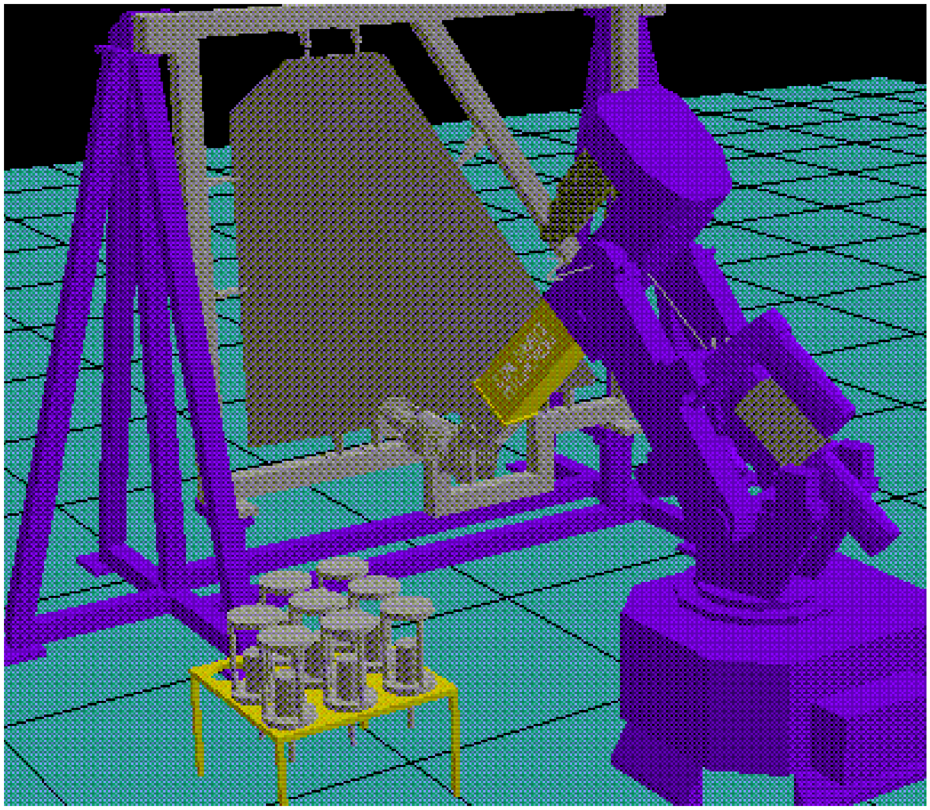


Figure 4-8. Example IGRIP Assembly Cell Model with Robot Model

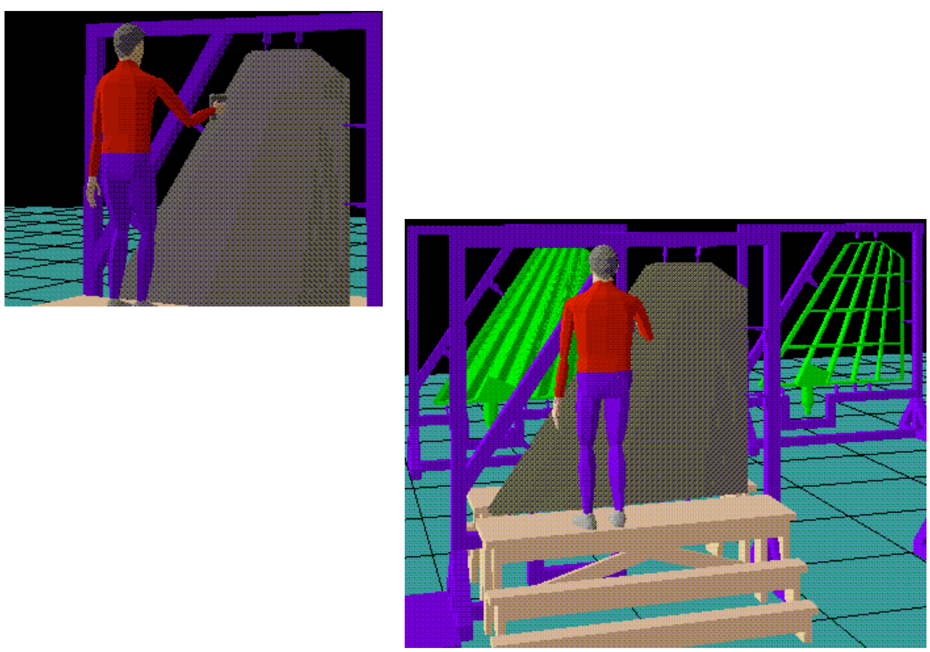


Figure 4-9. Example ERGO Assembly Cell Model with Human Model

2.4 Factory Simulation

During Phase I the entire F-16 Horizontal Stabilizer Assembly work cell was modeled. This model was developed using the Quest product by Deneb. This product provides interfaces for capturing product and tool designs directly from CAD systems. These interfaces include CATIA, ProE, UG and many other direct links. The ability to import IGES and STL files adds to the flexibility of the tool. In addition, the ability to directly import simulations from IGRIP/ERGO enables the factory floor to be modeled at a high level or detailed level (down to motions of machines and equipment). This helps solve some of the problems with levels of abstraction in product and process definition during the product development process. Also this enables a team approach, where a top level view of the factory can be established and the detail work cell definitions can be worked concurrently by other teams.

In terms of import capabilities from the Common Data Format, Quest imported process steps, times and resources used. Once the basic model was established, changes were made in external data bases or systems that ultimately provide data needed to run the simulation. The result is that simulation maintenance is minimized. Figures 4-10 and 4-11 show the extensive simulation developed for the Phase I demonstration.

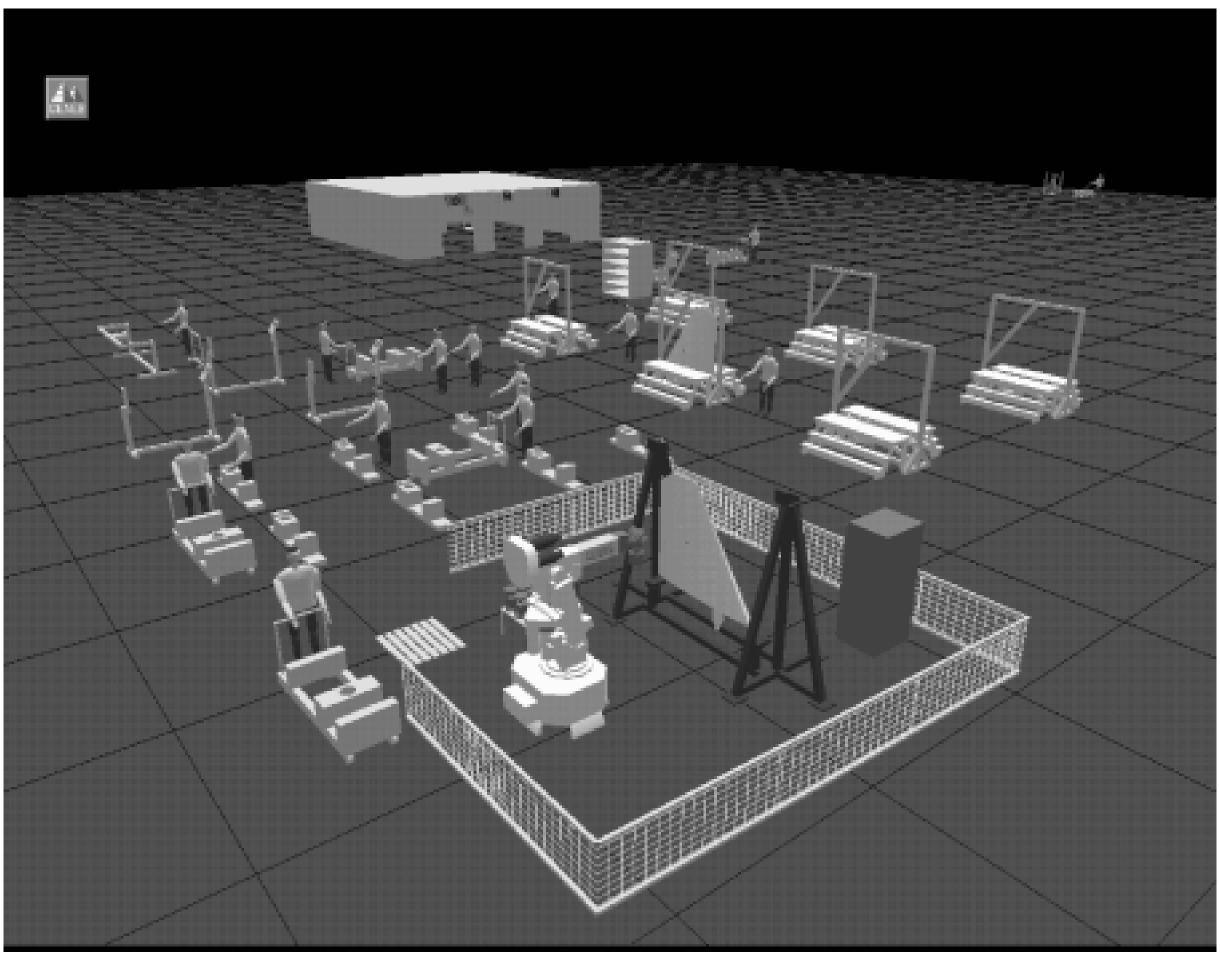


Figure 4-10. Example Factory Flow Simulation with IGRIP and ERGO Models Linked

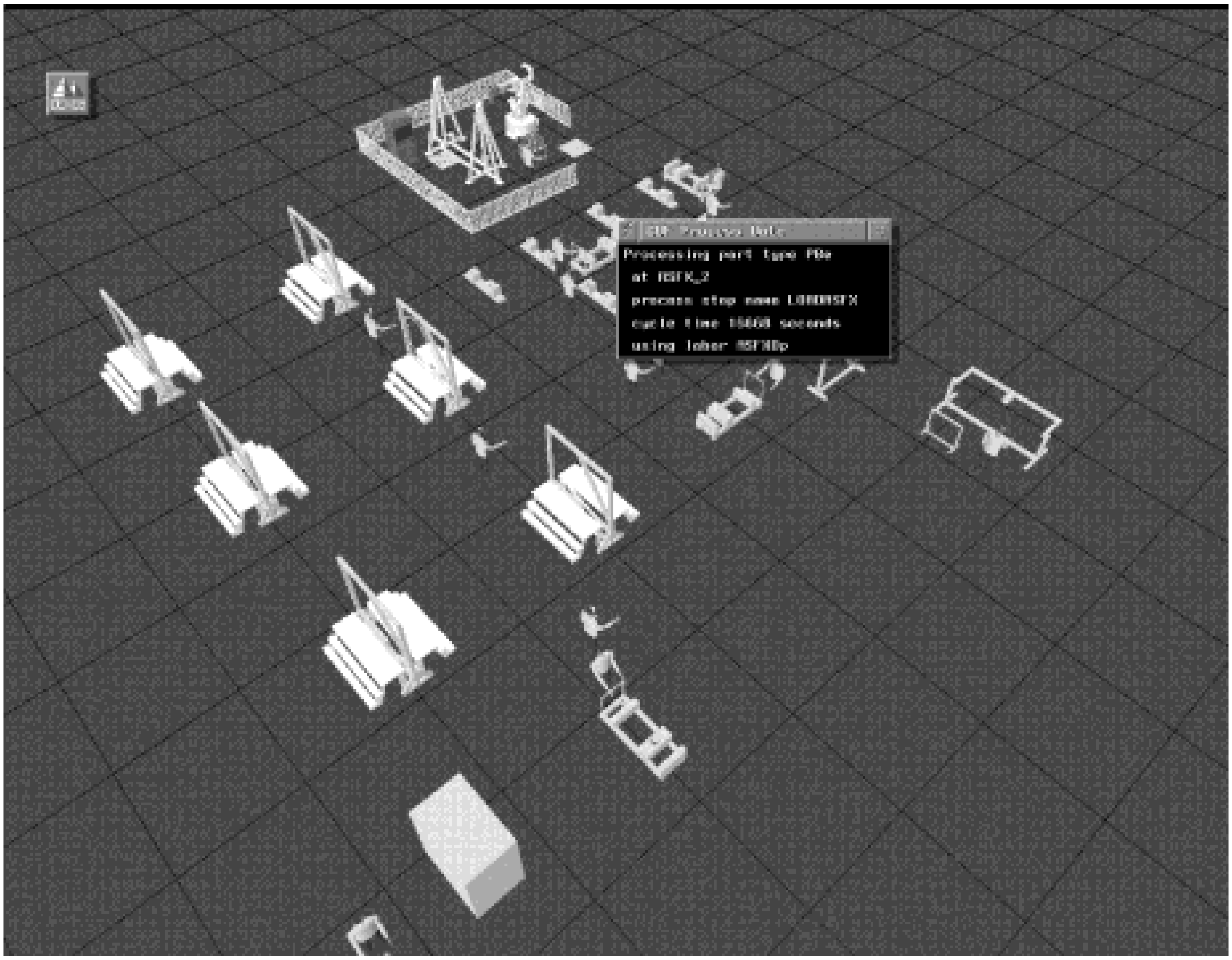


Figure 4-11. Quest Import Dialog Box and Animation

2.5 Work Instructions

One of the keys to getting past the implementation and maintenance hurdle for simulation technologies is making these technologies an integral part of the data process for the factory floor. The way the SAVE team chose to address this challenge was to create a set of macro work instructions directly from either the Quest or IGRIP/ERGO simulation tools. These instructions contain the part or component, the process, the part numbers, tool numbers and graphic images needed to support the production work instruction process. The idea was to maintain the work instructions in the simulation and in this way validate the instructions prior to making parts. In addition, the format was set up so that internal systems could easily import the work instruction file for future use.

The other aspect of the work instructions was that most simulation companies are providing run time licenses for their products at very low prices. These licenses run on PCs. This would enable the following concept to be implemented on the factory floor for minimal cost. A PC would be placed at each worker's station with the simulation loaded. The user will select the appropriate work instruction file and replay the simulation based on the work instruction file.

This allows the factory floor personnel to see the process before starting work. Figure 4-12 is an example of the progress from Phase I for the work instruction file.

```
WORK INSTRUCTIONS
********************************
TSK_OP,LOADASFX,236.8
PART(S)
pn#16T7462.pivot.assy

TOOL(S)
tn#188273

********************************
TSK_OP,LOADASFX,540.2
PART(S)
pn#16T7469.l.edge

TOOL(S)
tn#188273

********************************
TSK_OP,LOADASFX,857.2
PART(S)
pn#16T7466.cor.skin

TOOL(S)
tn#188273

********************************
TSK_OP,LOADASFX,857.2
PART(S)
pn#16T7483.aft.edge
pn#16T7482.tip

TOOL(S)
tn#188273
********************************
TSK_OP,DRILL,857.2
PART(S)
pn#16T7462.assy

TOOL(S)
tn#188273

IMAGE(S)
hor.area
```

Figure 4-12. Example Work Instruction File

2.6 Risk Assessment

The ASURE risk assessment tool was used to predict the probability of manufacturing a zero defect component based on manufacturing process characteristics. Models for assembly of both configurations, the detail part configuration and the robotic drilling process were developed. The tool uses a Monte Carlo simulation technique and the expected value, upper spec and lower spec to determine the estimates. Simulation results are shown in Figures 4-13 and 4-14. Ideally an S-shaped curve is developed with the upward sloping piece of the curve nearly vertical. This indicates a well-controlled process for which the results will be consistent. The user then must find creative solutions in changing the product or the process to drive the upward sloping portion further to the right. The import capability developed during Phase I imported the process plan and process characteristics from the CDF. If changes occurred during the iterative design process, the data in ASURE was highlighted so that the user could make the necessary changes.

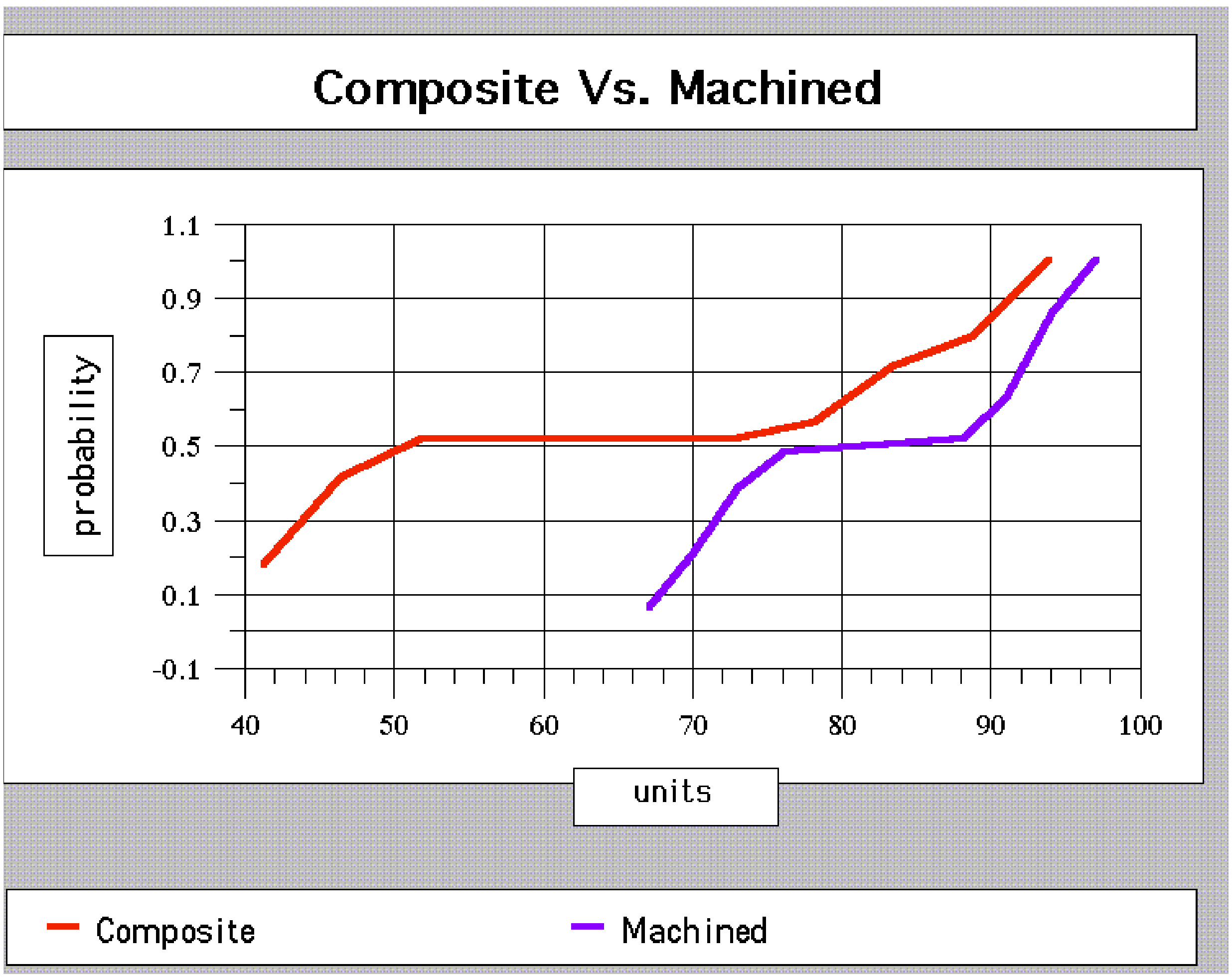


Figure 4-13. Example ASURE Model Results for Two Different Processes

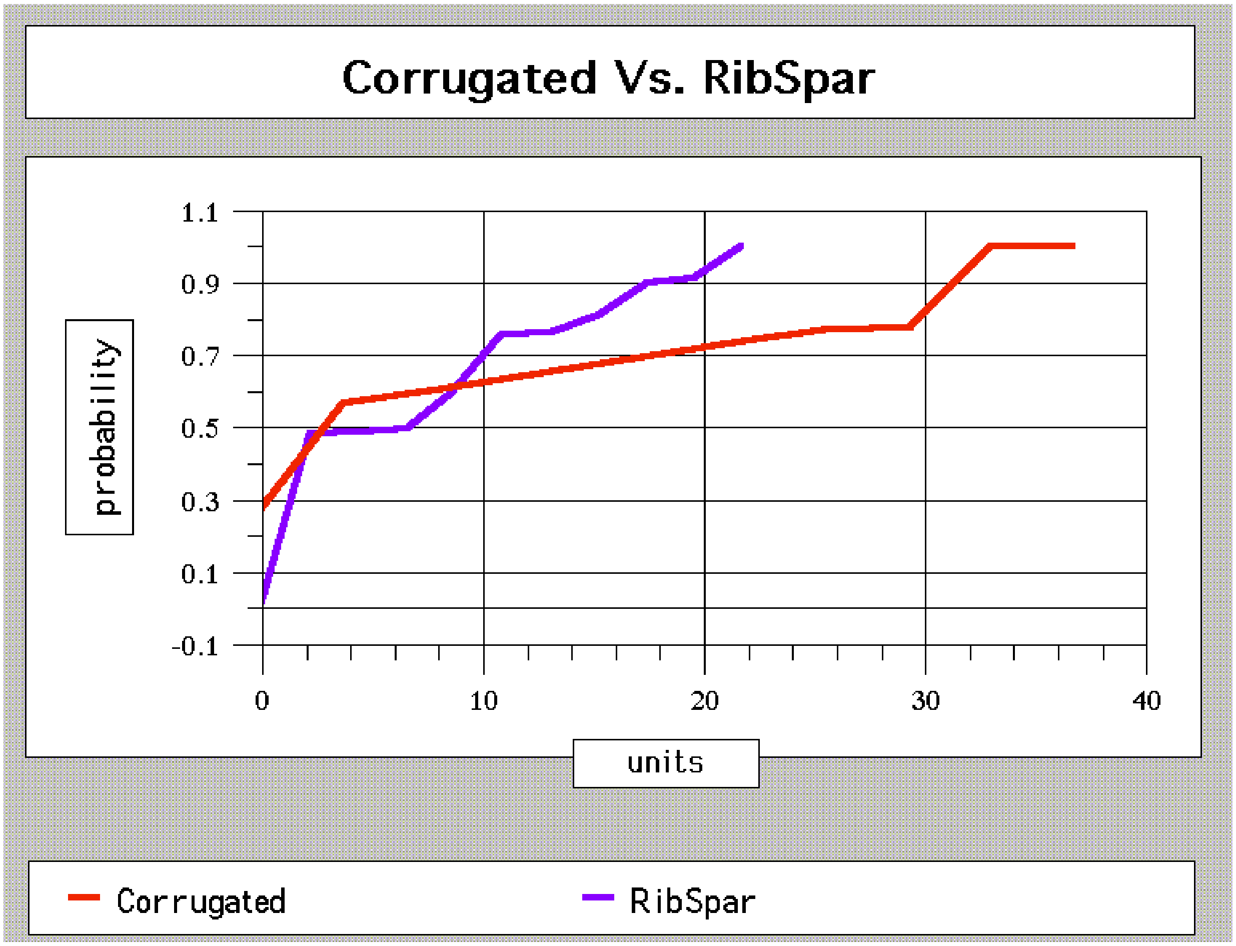


Figure 4-14. Comparison of Yield Results for Two Different Configurations

2.7 Schedule Simulation

In Phase I the schedule simulation tool was used initially to develop the proposed process plan for the components that formed the basis for the CDF. Use of this approach or the use of a process planning tool is necessary to perform this step. Both import and export capabilities were developed so that a baseline schedule could be generated, passed to other tools where the schedule would be refined (time for task) and then the schedule simulation was rerun to determine the impact on the factory. This tool also lets users import data from other systems, such as MRP, so the existing factory commitments can be considered in the simulation process. Examples of a process plan and schedule developed with the Factor/AIM tool are shown in Figures 4-15 and 4-16.

corrob	SETUP	Setup / Operation	Gen Set_up & Inspect Parts
	LOADASFX	Setup / Operation	Load parts into ASFX and drill
	REMVTOOL	Setup / Operation	Remove Tooling & CNSK Holes
	ULDPARTS	Setup / Operation	Unload parts deburr seal fastn
	MILLFAST	Setup / Operation	Mill fasteners & inspect
	LOCSKINS	Setup / Operation	Loc skins cleco scribe skins
	LIQSHIM	Setup / Operation	Remove skins clean liquid shim
	INSTLSKN	Setup / Operation	Install skns cleco instal DRFX
	MVTOROBT	Move	move from ASFX to Robot queue
	LDDRLFX	Setup / Operation	Robot Drill Skins
	DRILL	Setup / Operation	Drill horizontal stabilizer
	ULDDRLFX	Setup / Operation	Unload drill fixture
	MVTOSKNA	Move	Move from robot to skin attach
	REAMCNSK	Setup / Operation	Ream CSNK Holes
	DEBURR	Setup / Operation	Remove skns defod clean inspct
	INSTFAST	Setup / Operation	Seal load skins install fastne
	MVTOLE	Move	Move from skin attach to LE
	LOADASSY	Setup / Operation	Load box assy/retainers & dril
	INSTNUTP	Setup / Operation	Drill/CSK/Install nutplates
	INSTBOLT	Setup / Operation	Prefit/seal/load/install bolts
	INSTNAME	Setup / Operation	Spotface hls install nameplats
	MVTOINSP	Move	
	REMVPLY	Setup / Operation	Remove ply seal clean touchup
	INSPECT	Setup / Operation	Load assy for chk gage/inspect

Figure 4-15. Example Process Plan Developed in Factor/AIM and Exported to the CDF

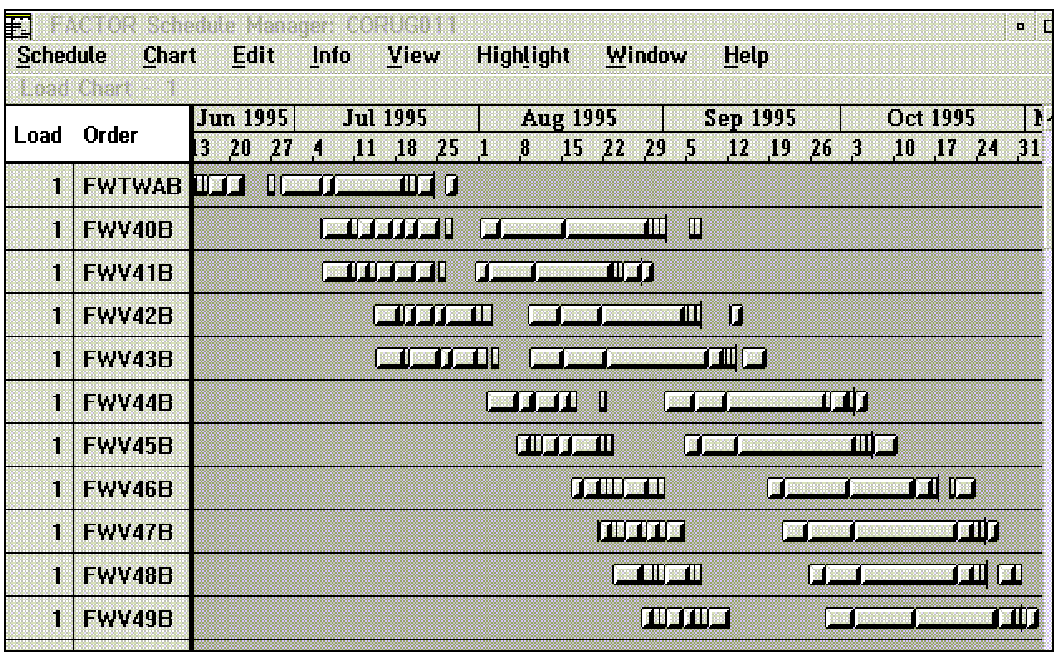


Figure 4-16. Example of Schedule Produced by FACTOR/AIM

2.8 Manufacturing Capabilities

Figure 4-17 is a screen capture of the JMCATS tool and a model that was set up specifically for the Phase I demonstration. The process technologies that are presented on the right hand side of the screen shot were automatically imported from the CDF through an interface developed by GRCI.

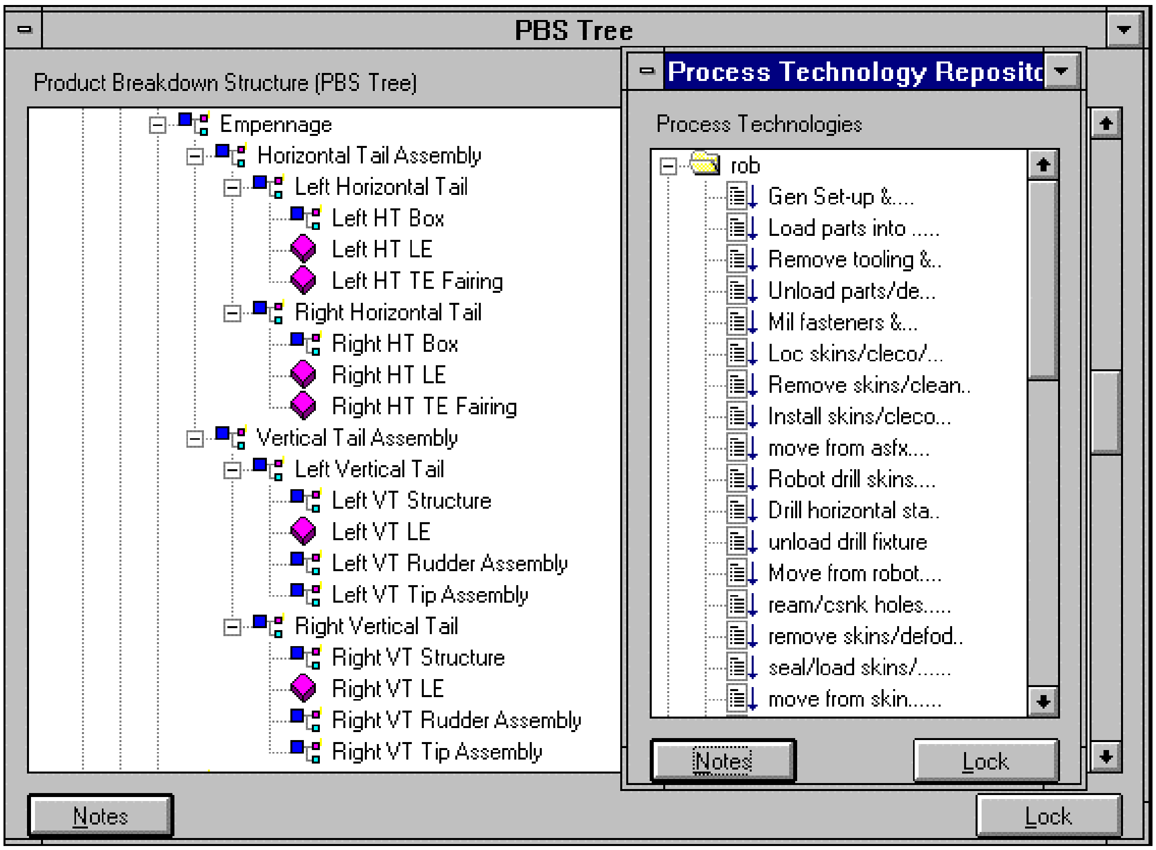


Figure 4-17. JMCATS Model for the Horizontal Stabilizer Assembly Process

3.0 Demonstration/Trade Studies

The SAVE Phase I demo involved the F-16 horizontal stabilizer. This design modification actually occurred in the early 80’s; however, the events associated with the change provided an excellent example of how the SAVE tool suite could be used in an IPT setting. The original F-16 horizontal stabilizer was a honeycomb core bonded panel assembly and an engineering redesign required an increase of 20% in stabilizer area. The results of stress and weight analysis were sufficient to rule out an increased area honeycomb core bonded panel assembly early in the design evaluation. For the purposes of the SAVE demonstration, the actual corrugated spar construction and a hypothetical rib spar design were used to develop assembly process trades, manufacturing process refinements, and detail parts trades. Figure 4-18 provides an overview of the overall SAVE Phase one decision process and final selection of the corrugated spar assembly.

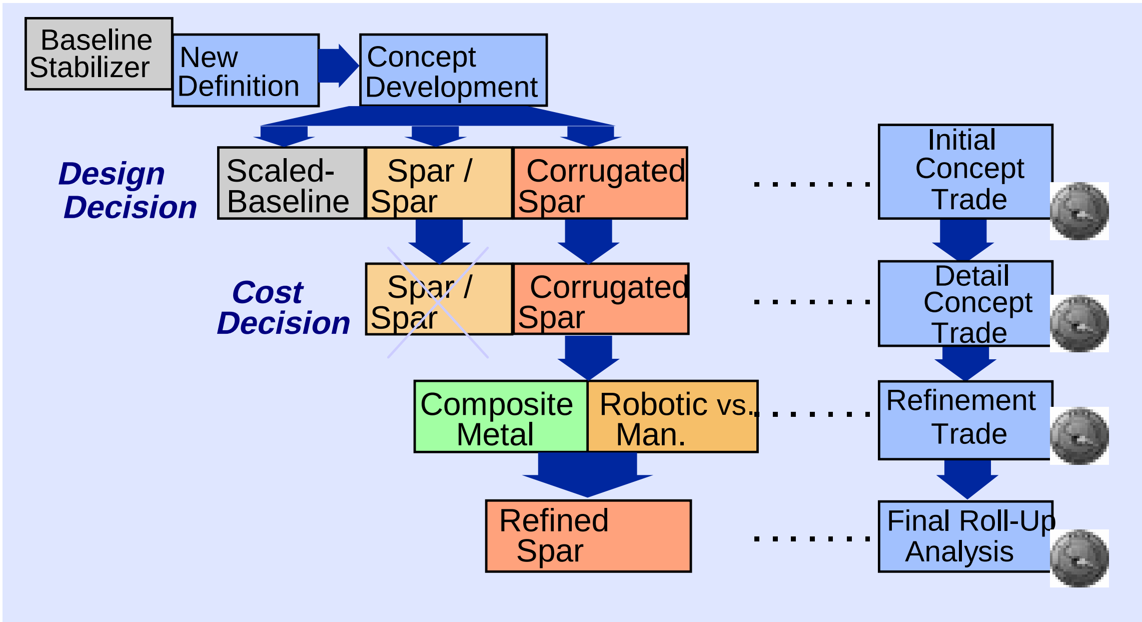


Figure 4-18. Overview of the Phase I Decision Process

3.1 Structural Concept Selection

During the structural concept selection activity, three candidate designs were proposed: a scaled up version of the original honey comb core bonded panel assembly, a rib spar design with attached composite skins, and a sheet metal corrugated spar design with attached composite skins.

As already mentioned, the engineering stress analysis results were sufficient to rule out a scaled up version of the original honeycomb core bonded panel assembly early in the design process. Subsequently, the two remaining alternatives were given preliminary process plans and evaluated in terms of cost, schedule, and risk. Tools used to perform this task include ergonomics of the manual assembly operations, discrete event simulation to determine process times resource requirements, and overall span, and cost assessment to determine the cost for both options. In this comparison using manual assembly techniques, cost and schedule were the main factors for choosing the corrugated spar over the rib spar configuration (structural concept selection) since the risk would be comparable for both options when using similar assembly fixtures, manual drilling, and fastening techniques. The preliminary simulation results indicated that:

- The rib spar design would require more assembly fixtures and assembly labor than the corrugated spar design to meet schedule span requirements.
- The rib spar design would require more detail components and associated detail fabrication costs.

3.2 Manufacturing Method Trades

Once the corrugated version was selected, manufacturing assembly plan modifications including robotic drilling were considered. The drilling options were evaluated by comparing ergonomic analysis of the manual drilling process to IGRIP analysis of the robotic drilling process. After comparing the results of the two simulations, a significant reduction in span time for the composite skin drilling/countersink operation was indicated for the robotic drilling process. Additionally, risk assessment of manual versus robotic drilling/countersinking of the composite skins indicated that significantly more rework would result if the manual drilling process were used.

In summary, cost and risk were the primary factors for selecting robot drilling over manual drilling for the composite skin attachment process (manufacturing method trades) for the following reasons:

- Robot drilling provides an overall reduction in cycle time for the drilling operation thus reducing cost.

- Robot drilling provides a much smaller variance with respect to the nominal countersink depth requirements, which reduces the need for fastener and surface rework (milling and filling) as compared to the manual drilling process.

3.3 Detail Part Trades

Once the corrugated version was selected, detail part trades were performed on various components of the horizontal stabilizer assembly. The assembly of the horizontal stabilizer requires the attachment of a sub assembly (leading edge assembly) to the stabilizer during the final assembly process steps. This sub assembly is a bonded panel design and a material compatibility problem with one of the baseline components (machined root rib) and the leading edge sub assembly was anticipated. In this instance risk was the driving factor. No schedule impact was indicated, however additional cost was estimated by the subsequent cost assessment. A machined aluminum root rib is less expensive to fabricate than a composite root rib, but potential material compatibility problems with the next assembly justified the use of the composite root rib for this application.

3.4 Summary of Results

The Phase I demonstration focus components consisted of elements of the F-16 Horizontal Stabilizer. The ability to assess manufacturing impact of design decisions was shown on the down selection of structural configurations. The results of this downselect are shown in Figure 4-19.

After down selection to a single concept, the assembly process was further studied to determine the potential for replacing manually drilled operations with robotically drilled operations. The results are shown in the Figure 4-20.

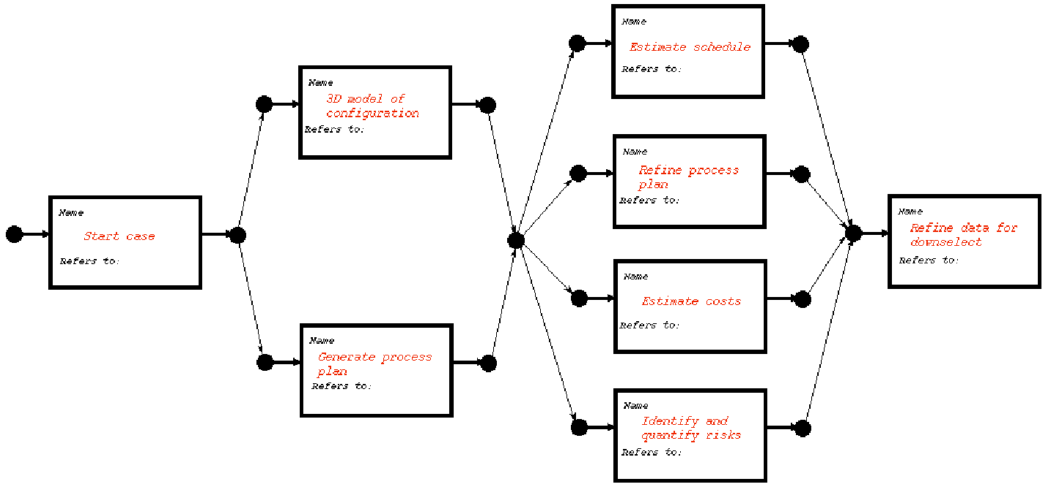


Figure 4-19. Decision Process for Structural Downselect

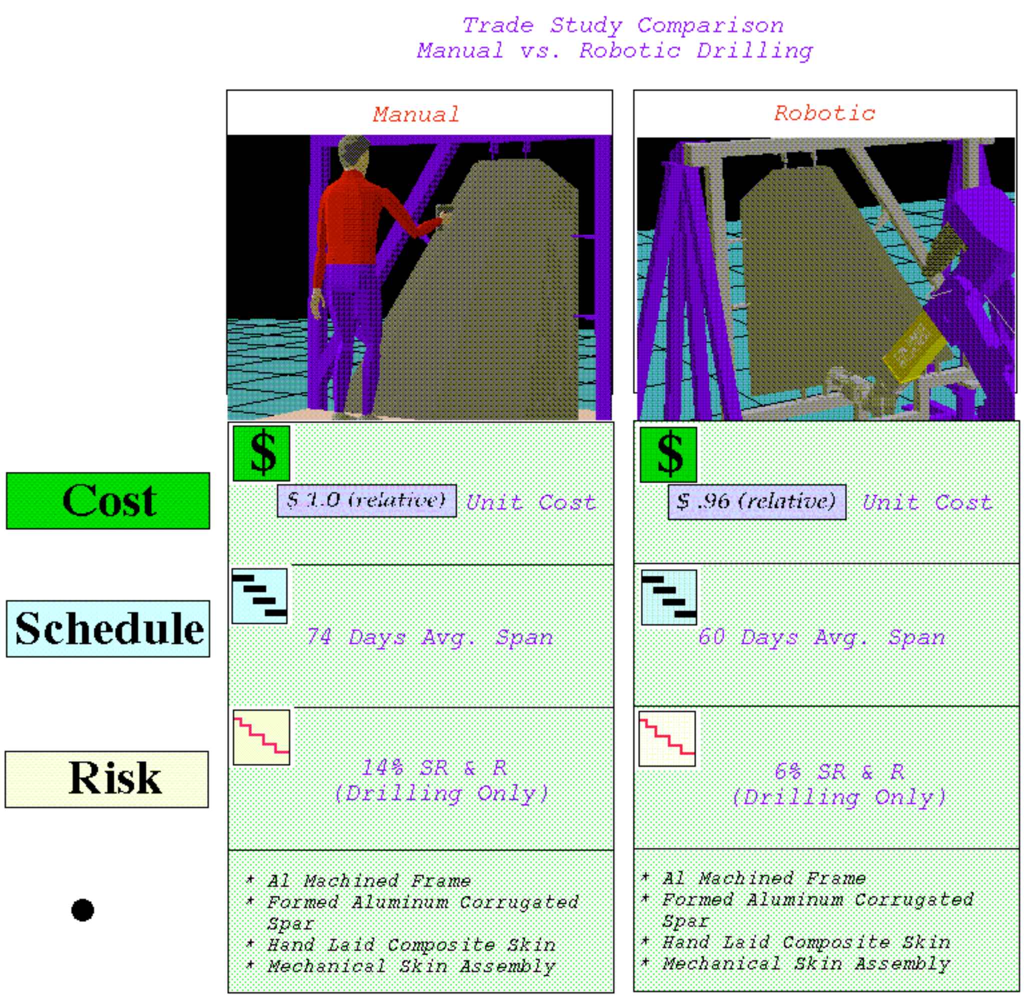


Figure 4-20. Robotic versus Manual Drilling Results Comparison

The final assessment performed as part of the Phase I demonstration compared material/process selections for detail part fabrication. The study consisted of trading the cost, schedule and risk of machining a rib to building the rib up out of composites. The results are shown in the Figure 4-21.

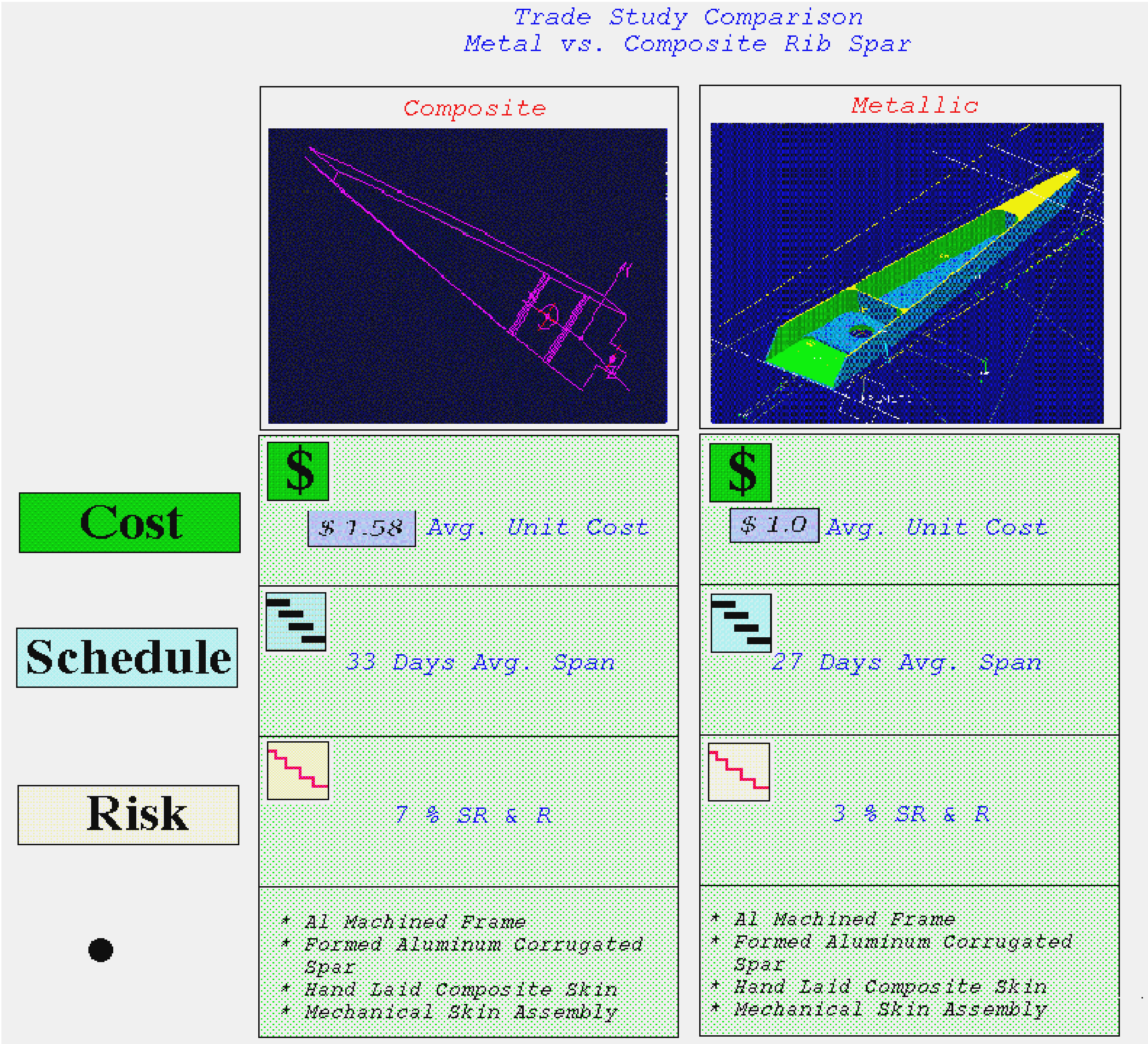


Figure 4-21. Machined Versus Composite Hand Laid Up Composites

3.5 Presentation/Documentation of Demonstration Scenario

The actual demonstration phase of the SAVE program consisted of a video and a live demonstration. The video was presented at the JSF Industry days symposium in August 1996. The live demonstration occurred during the Defense Manufacturing Conference in December 1996. The demonstration for the IP/PTs was conducted in the SAVE laboratory. The laboratory was setup to facilitate the demonstration of the SAVE technologies, and is shown in Figures 4-22 and 4-23.

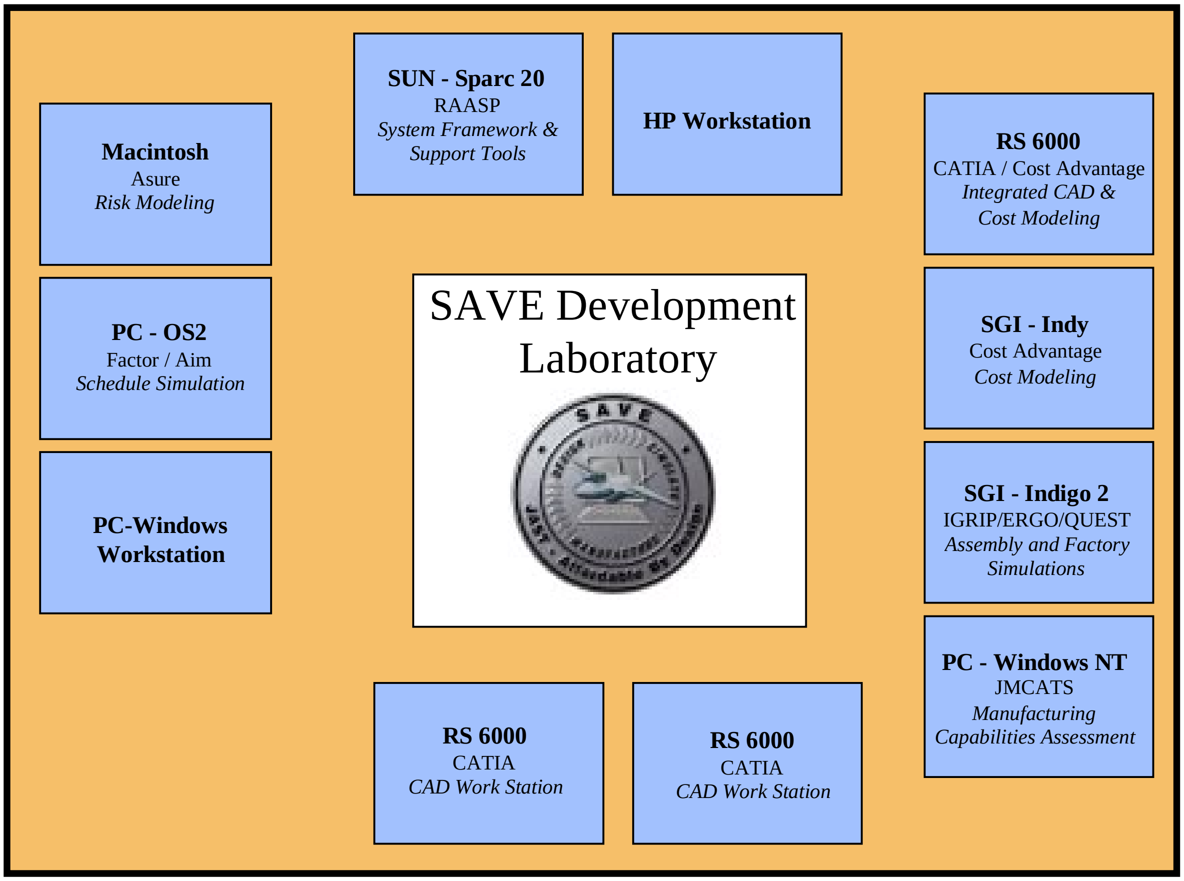


Figure 4-22. SAVE Development Laboratory Layout

The laboratory consists of seven networked hardware devices. The devices do not have to be in the same room, building, city, state or country. The infrastructure enables the rapid transition to production for a geographically dispersed team.

Figure 4-23. The SAVE Laboratory

Chapter 5

Phase II Interim Demonstration

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 Overview

The three demonstrations are a vital cornerstone of the SAVE program plan These demonstrations test the SAVE developed infrastructure and tool integration approaches. But possibly more important is their role in validating that the use of SAVE and its manufacturing simulation tools can achieve the significant affordability impact projected for the selected metrics. The purpose of the demonstration portion of the SAVE program is to define, model, and execute real world scenarios that demonstrate the integrated capability of the virtual manufacturing applications within the SAVE tool suite.

Progress in implementation of the SAVE program was highlighted at the Interim Demonstration, discussed below and shown in the context of the SAVE demonstration plan in Figure 5-1. Each demonstration consists of an analysis using real aircraft designs and data, presentation of results and a video. The demonstrations show how the virtual manufacturing and simulation tools selected by SAVE can be used to influence the product design and manufacturing approach to reduce time and cost. The Interim Demonstration showed progressive improvement in capability and usability, and how the tools can be used for different types of analysis. The focus of this demonstration was on validation of the CORBA-based integration infrastructure on a realistic, non-trivial design problem. The problem described in detail below resulted in a manufacturing process plan containing 175 operations, which was felt to be representative of the scale of problems to be addressed in typical design trade studies using SAVE.

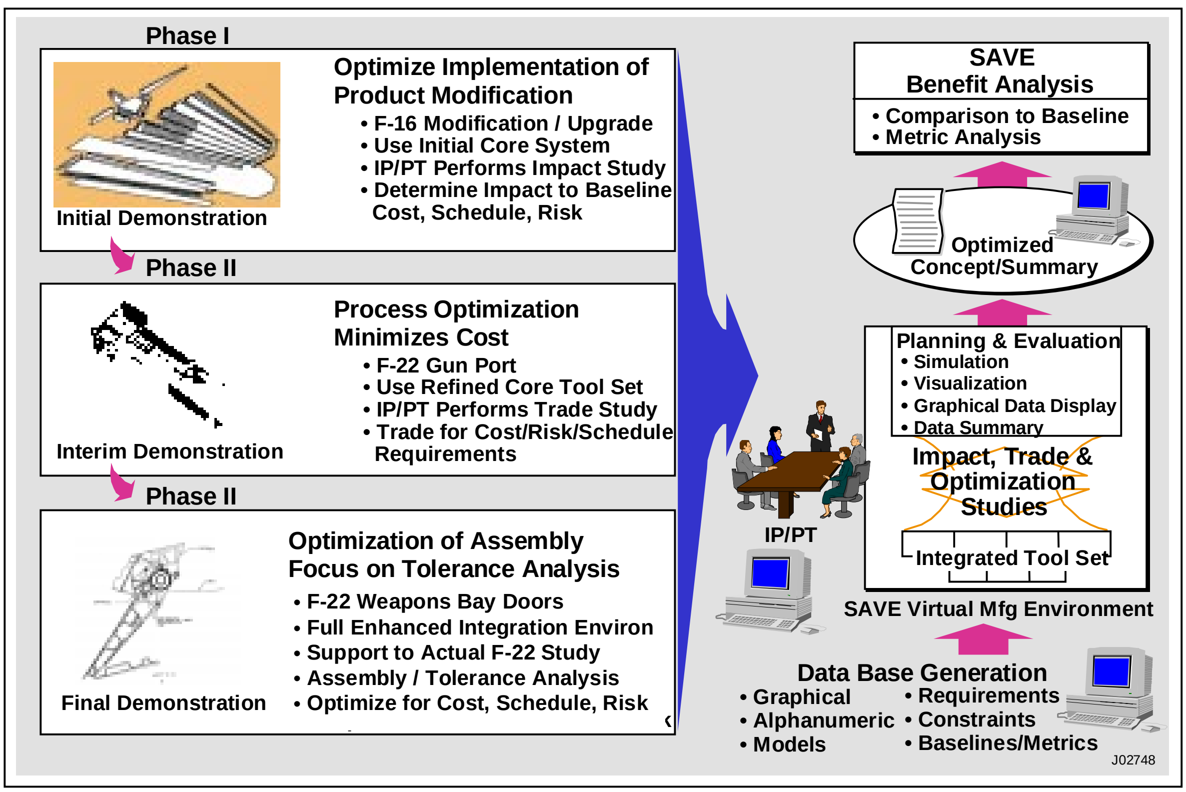


Figure 5-1. SAVE Planned Demonstrations

2.0 Demonstration Selection Criteria

The primary activities of the Demonstration Team for the Interim Demonstration were:

1. Defining the demonstration and creating the corresponding computer models

2. Determining what the input/output data requirements are for each tool from the user's perspective and testing the vendor tool interfaces.

Criteria used to select a candidate for the Interim Demonstration were:

- Structural assembly – To demonstrate capabilities of all tools within SAVE suite,

- Detail part trade studies within the assembly – To take full advantage of SAVE knowledge base development,

- Upcoming redesign effort – In order to have an impact on an existing aircraft program.

Of the several candidate design projects evaluated, the F-22 Gun Port assembly, shown in Figure 5-2, best met the above criteria and was chosen for the Interim Demonstration.

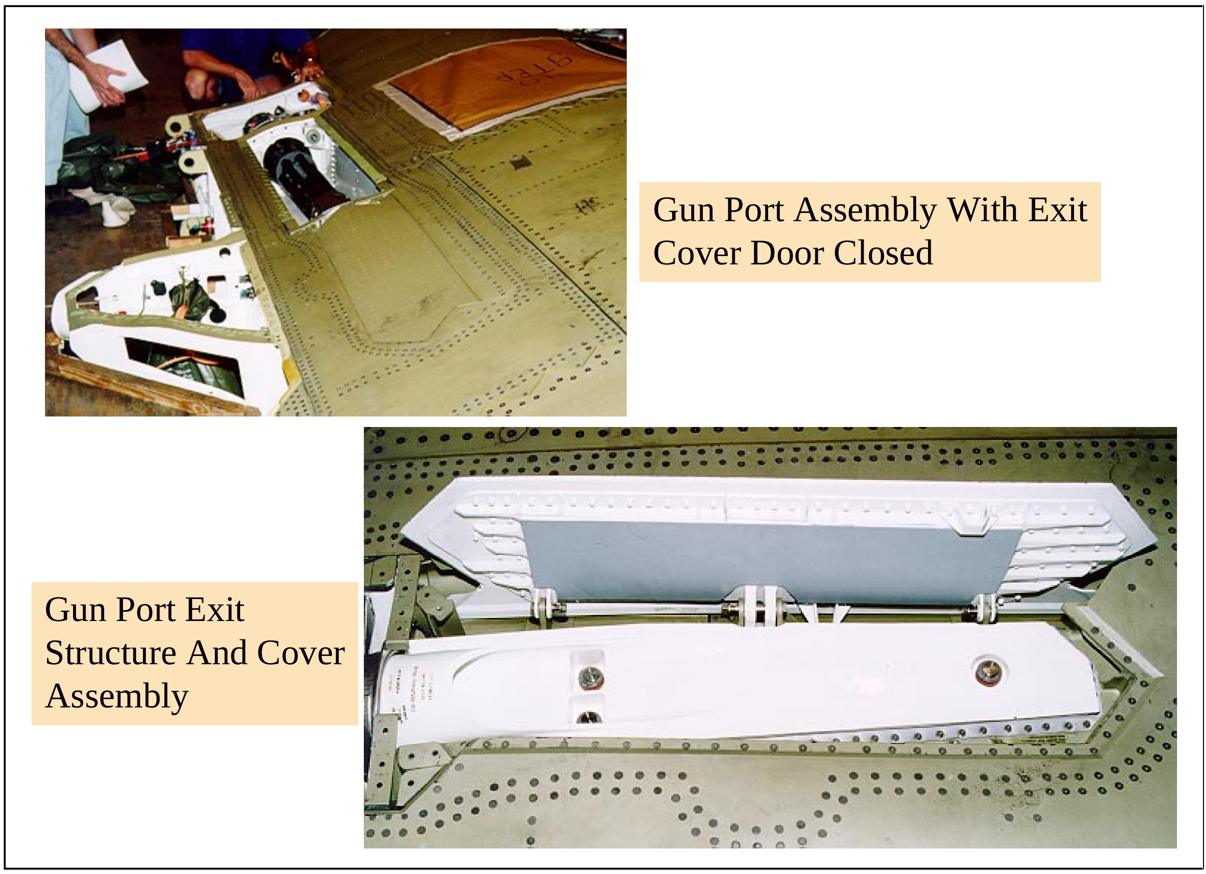


Figure 5-2. F-22 Gunport

Residual material from the F-22 gun blast was eroding gun port structure and forward surrounding skin. Observation of the assembly area indicates potential improvements to the overall gun port assembly operation through possible changes to assembly sequence/strategy, fastener installation methods, and part count reductions.

3.0 Interim Demonstration Scenario

The Interim Demonstration trade study process and demo scenario is illustrated in Figure 5-3 and is described below. The Phase II Interim Demonstration for the F-22 Gun Port assembly

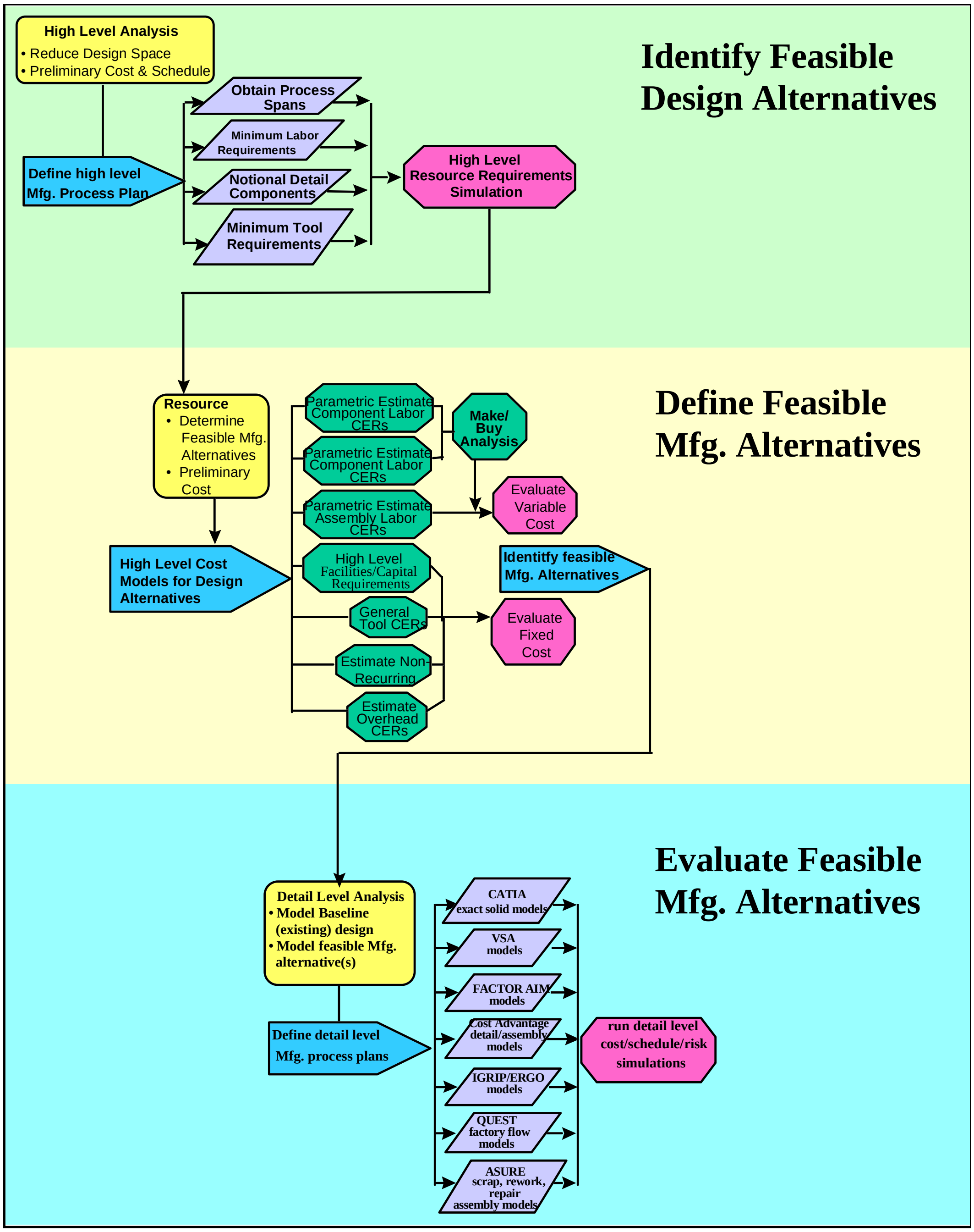


Figure 5-3. Overview of the Trade Study Process

compared the existing baseline design with feasible design alternatives. Additionally, manufacturing trades were performed to evaluate possible modifications to the present substructure. This demonstration showed how cost, risk and schedule can be traded in the early stages of the redesign process. This is the critical time when the greatest opportunities for cost savings can be realized.

The Demonstration Team worked with F-22 Structural Design IPT to define assembly and detail part trade studies for use in the Interim Demonstration. They planned to initially evaluate three to four assembly concepts, at a higher level, and downselect to two concepts based on cost and span time analysis.

The two final candidates, as well as the baseline, were modeled at a much more detailed level to assess manufacturing impacts from each of the SAVE tools. In additional to cost and schedule information, the detailed analysis included detailed geometry models, assembly tolerance analysis, factory flow visualization, ergonomic modeling, and risk analysis. The analysis made use of the direct interface between the CAD and cost analysis systems to extract required geometric information for detailed part costing.

Data mapping of all required manufacturing data into the SAVE Common Database was performed to assure that all data fields had been defined. In addition, the Demonstration Team tested progressive releases of the vendor tool interfaces as they become available.

The selection of a demonstration subject was critical to the successful completion of the SAVE Phase II Interim Demonstration objectives. Assembly trade studies were required to evaluate whether a single or split skin concept was the best option in terms of performance, cost , schedule, and risk. In this study, material considerations and tolerance management were key parts of the analysis. These questions were addressed through detail part trade studies of various material concepts and configurations. Alternatives to the baseline assembly process were investigated to assess possible benefits from assembly sequence modifications and/or redesign of some of the substructure.

The existing (baseline) F-22 gun port assembly was modeled by all tools to a high level of fidelity to support subsequent redesign trades. The baseline factory layout supporting the gun port assembly was simulated to a high degree of fidelity so that potential impacts resulting from the selected redesign concept could be properly identified and minimized. The baseline F-22 gun port models were modified to analyze subsequent redesign concepts. High level trades were performed by the cost and schedule tools to reduce the feasible design alternatives into a manageable set of manufacturing alternatives.

The Phase II Interim Demonstration was developed to show a consistent parallel analytical process when comparing the baseline process to the optimal manufacturing alternative redesign process. It showed an increased use of all tools introduced during the Phase I demonstration. It also demonstrated tool integration into the SAVE object oriented data model environment and emphasized the benefits of data reuse and configuration control (Figure 5-4).

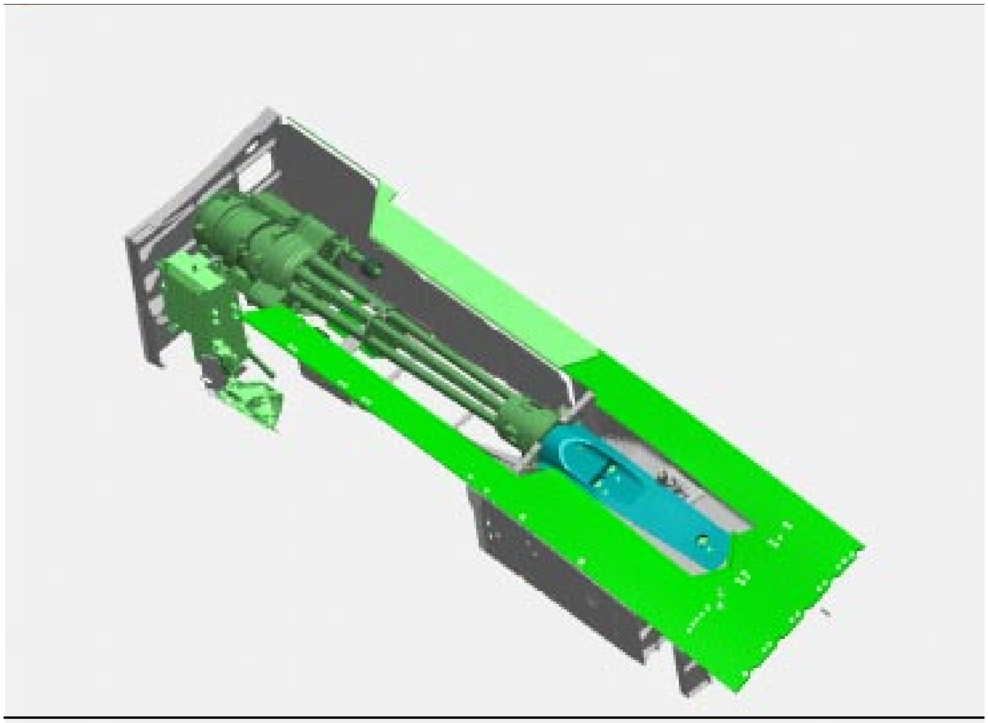


Figure 5-4. Solid Model of Existing Gun Port Assembly

4.0 Tool Usage

An accurate process plan was the fundamental data required to begin the SAVE process and supply SAVE applications. Therefore, considerable time was spent developing the baseline process plan. Actual time was spent in the F-22 assembly area understanding; what the current planning defined as Work Instructions; and if those Work Instructions accurately represented the process of assembling the baseline gun trough. As might be expected, the Work Instructions were not the same as the actual assembly process. A result of this research was development of a baseline process plan derived from the actual shop floor assembly process. This process plan was used to extrapolate an alternative process plan.

The initial process plan was simply a sequential list of manufacturing/assembly instructions. Team members were aware this sequential structure was not realistic with regard to real world process plans or effective for managing process data. However, basic data was required for software testing and maturing. The actual process plan implemented to support the Interim Demonstration was a more structured three-tiered indentured process plan consisting of 176 manufacturing operations. Process Plans were initially loaded into the SAVE Data Model using FactorAim, a discrete event simulation tool from Symix.

4.1 Symix FactorAim

FACTOR AIM functioned in two roles during the demonstration. First, FACTOR AIM was used to enter the process plan into the SAVE database. Second, standard FACTOR AIM functions were used to simulate a production schedule by applying anticipated production rates for the F-22 Mid-Fuselage Assembly. As the gun port installation is not a critical path assembly operation, the gun port installations (by ship-set) were constrained by span expressions for WBS 1233, WBS 1232, and WBS 123. A set of mathematical expressions were used to synchronize the start and required completion of the gun port installations for each ship set:

Through FACTOR AIM, the SAVE Program illustrated the first assembly process model using the current production tooling resources (one W 13000 floor fixture, one roll over sub assembly fixture, and two final assembly stations). It was assumed that two assembly operators would be dedicated to the gun port installation task. Simulation of the process demonstrated projected production rates could not be met with the current factory layout (Figure 5-5). Notice that loads 094 through 339 are still in process at the end of the simulation 11/16/12. The magenta color of W 13000 indicates that this tooling resource was "blocked" at the end of the simulation. Through FACTOR AIM, the SAVE Program also illustrated the number of required floor tools and final assembly stations to meet production rate deliveries (Figure 5-6). Notice that loads 331 through 339 are still in process at the end of the simulation 11/16/12. The magenta color, visible in the screen image, of all W 13000 floor fixtures indicates that these tooling resource were "blocked" at the end of the simulation

FACTOR AIM was also used to provide a schedule roll-up once all database activity was completed. This schedule roll-up was in the form of a detail Gantt chart illustrating Start Dates,

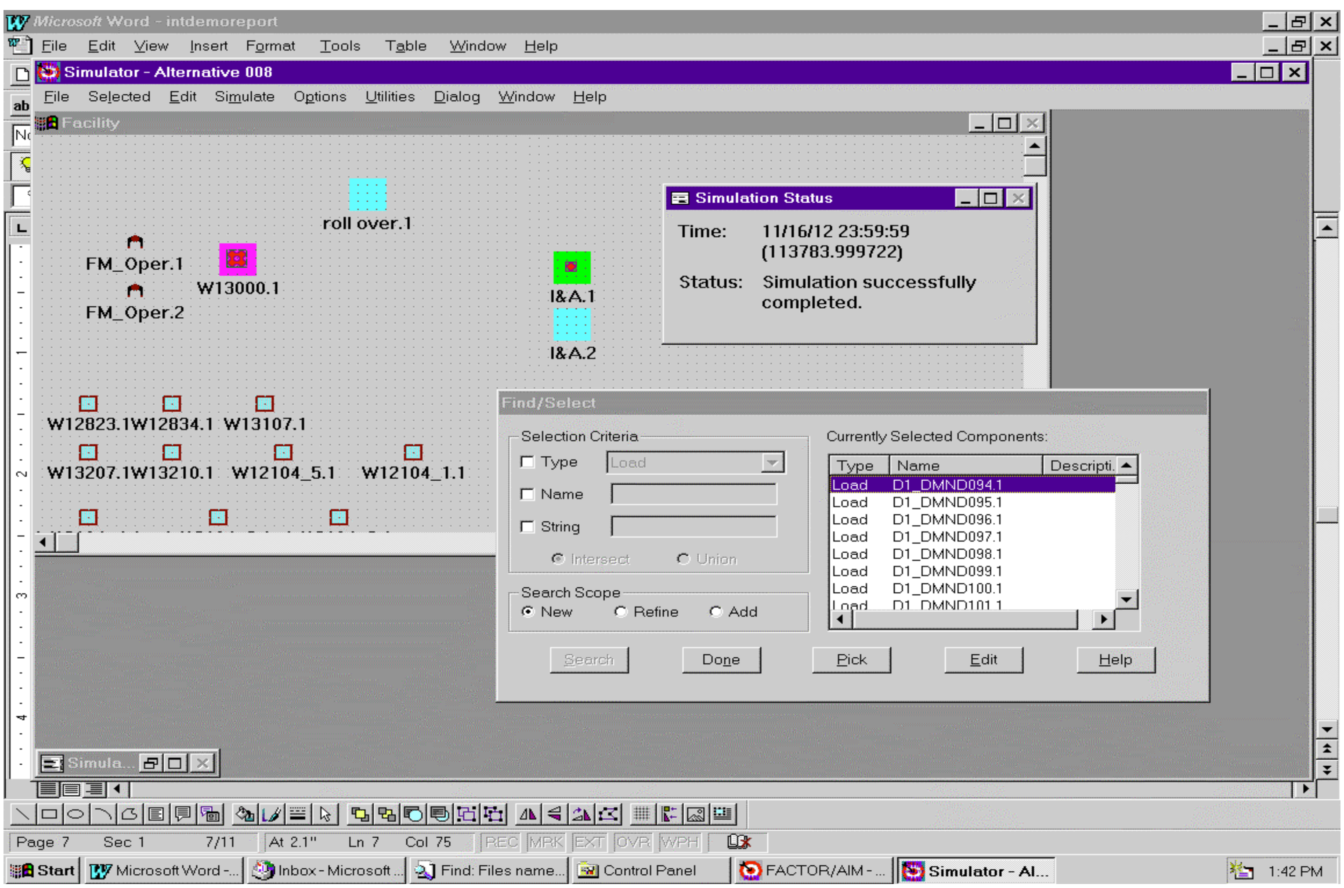


Figure 5-5. FACTOR AIM First Model for F-22 Gun Port Installation

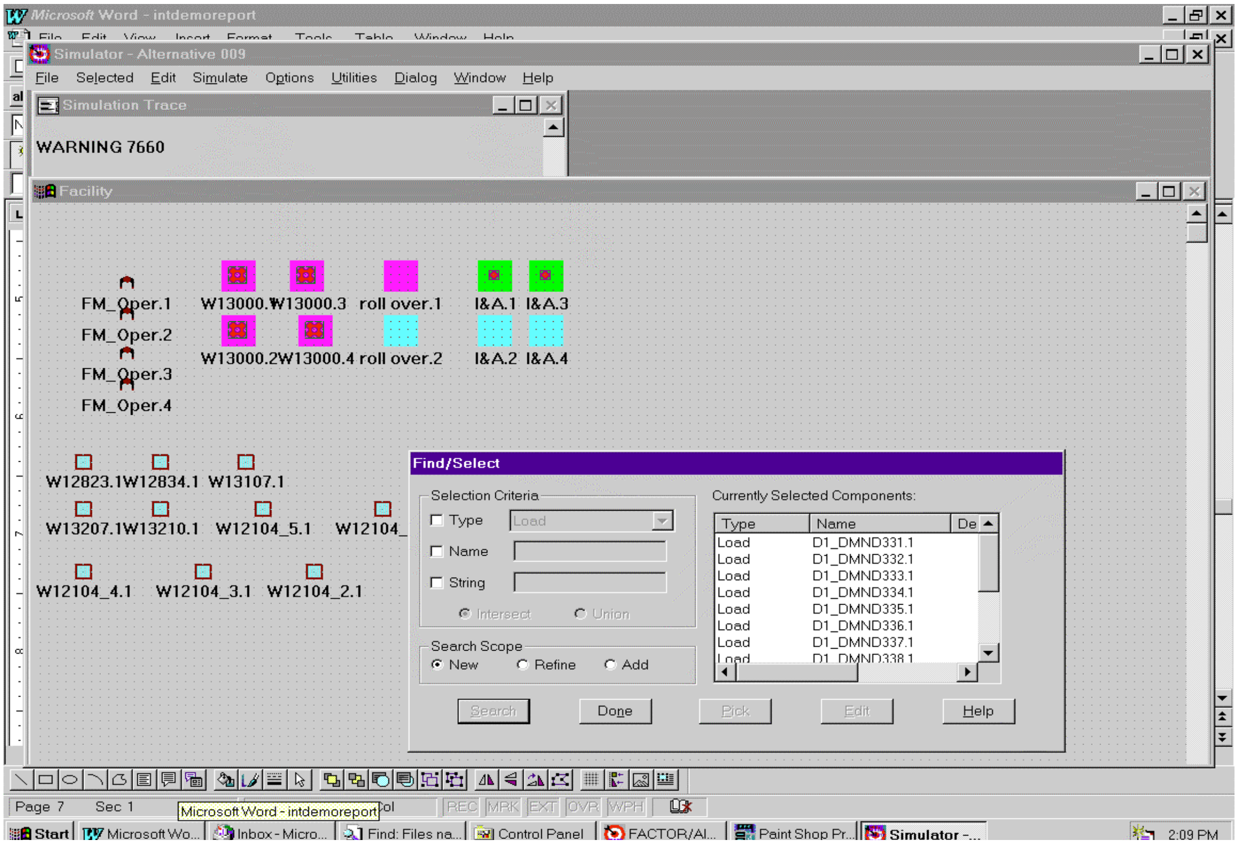


Figure 5-6. Second FACTOR AIM Model for F-22 Gun Port Installation

Times in Station and Completion Dates. This information was generated based on the Production Schedule, updated process times from the SAVE database, and available resources (e.g., tools, etc.). Cost Advantage assembly model used the defined process plan and process steps such as locate, drill ream, and install to "roll up" the time requirement calculations. Each process step name or process feature is a unique process model function.

A minimum requirement to invoke an assembly process feature was the quantity (for example: number of parts, number of holes, or quantity of fasteners). In the case of Drill Ream process, the quantity parameter was used to meet the minimum requirement (Figure 5-7). The quantity parameter could have been provided by interrogation of a CAD model, user input, or statistical estimation. For the SAVE Interim Demonstration, the Drill Ream quantity was extracted from the process plan.

4.2 Deneb Robotics IGRIP

The IGRIP simulation package from Deneb Robotics, Inc. was used to simulate manufacturing operations within the SAVE process plan. The IGRIP package, a "time based" simulation system, that is ideally suited to developing visualizations of manufacturing processes, modeling workcells and automated equipment, determining cycle times, detecting collisions, and performing ergonomic analysis of manufacturing operations. For the SAVE Interim Demonstration, IGRIP was used to model the entire process of assembling and installing the F-22 gun trough. This “big picture” (Figure 5-3) provided the capability to visualize the entire process plan in a matter of minutes. The sequence of the assembly process could be easily modified or rearranged using the ASSEMBLY option within the IGRIP package.

The flexibility of IGRIP allowed it to be used for modeling processes at whatever level of detail was required. In addition to visualization of the entire process plan, IGRIP was used to model a single operation within the SAVE process plan. The particular operation chosen was a drilling operation which created 28 holes for attaching the gun trough to the under structure. This highly detailed simulation was developed using both the ERGO and ASSEMBLY options of IGRIP and featured an operator hand drilling the 28, 0.191” diameter attach holes (Figure 5-7).

The parts and tools used, in both of the IGRIP simulations, were created by translating engineering and tooling CATIA models into an IGRIP readable format. The geometry was then brought into the simulated workcells and placed in the proper locations. The ASSEMBLY option within IGRIP was used to create the trajectories the parts and tools, including the hand drill, followed during the simulations. The ERGO option was then used, in the drilling model, to program the “ERGO man” to manipulate the drill.

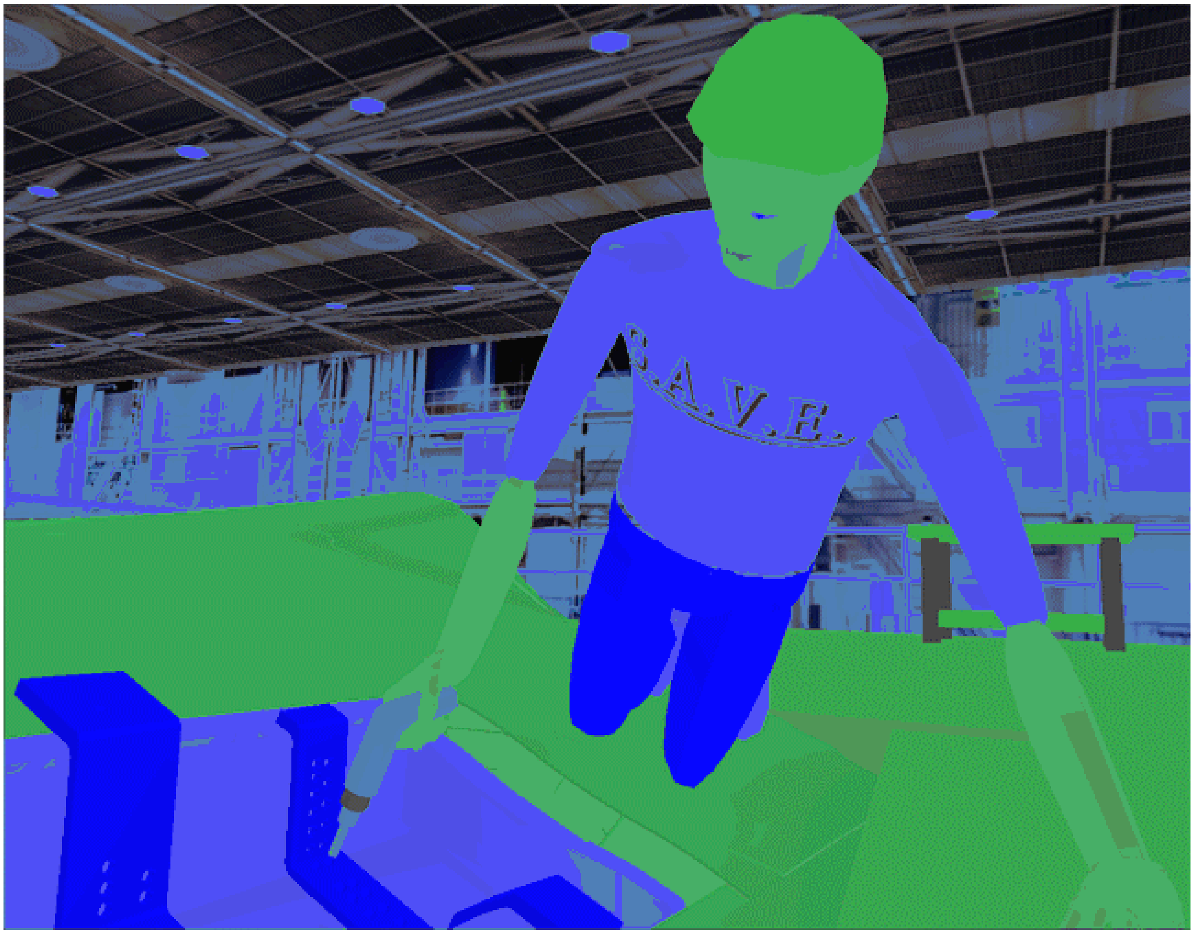


Figure 5-7. Screen Capture From the Manual Drilling Model

A SAVE-compliant "wrapper" program was developed by Deneb to provide an interface between IGRIP and the SAVE database. This CORBA based interface allowed IGRIP to read any of the operations from the process plan contained in the database. A refined span time for the operation was then generated by running an IGRIP simulation of the operation and writing the time back to the database. Part and tool information could also be verified to ensure the integrity of the process plan. The drilling simulation produced a span time for manually drilling the 28 attach holes. The span time was then written back to the SAVE database.

4.3 Deneb Robotics QUEST

During the Phase 2 development, the SAVE QUEST Interface was matured into an interactive CORBA client with the SAVE Database. The QUEST Interface was also successfully integrated with the Workflow Manager.

The major enhancements of Quest's functionality developed during Phase 2, shown in Figure 5-8, were:

- Browse and create process plans in the SAVE database, including browsing through different levels of a nested process plan.
- Display operations, tools, personnel, calendars, and shifts associated with process plans.
- Create a calendar for process plans.
- Create and modify shifts, breaks, tools, personnel, and operations within process plans.
- Add tools, personnel, and precedent operations to an operation.
- Create parts to associate with operations.
- Write tool and personnel utilization to the SAVE database.
- Parse process plans from the SAVE database (i.e., create a complete QUEST model from a process plan).

By the end of the Phase 2 development, the QUEST Interface could dynamically create a brand new model of the F-22 Gunport Process Plan from information written to the SAVE database by either the FACTOR/AIM Interface or the Cost Advantage Assembly Interface. This capability was demonstrated at the Interim Demonstration and allows QUEST models to be built in as little as 10% of the time it takes to manually build the model, shortening the task from hours to minutes.

A model was built based on the current F-22 Production Schedule to analyze the number of tools and workers required to support the deadlines in that schedule. This work was concurrent with a similar model building effort in FACTOR AIM. Additional data was derived from available schedule data on the current pre-production mid-fuselage sections. The QUEST model predicted that four Final Mate Fixtures and four I-and-A Assemblies would be required to meet the production schedule. This prediction agreed with the current number of fixtures and assemblies

Figure 5-8. The QUEST Interface Toolbars

planned. This QUEST model also predicted that only one Roll fixture will be needed, even though two are planned.

This model illustrates some of the predictive capabilities offered by SAVE (Figure 5-9). The model also illustrates how multiple tools can use the same information from the database and verify each other's results. The Final Mate Fixtures appear on the left and the I/A Assembly Stations appear on the right. The two roll fixtures are located on the two bottom left Final Mate Fixtures.

Figure 5-9. QUEST Model of F-22 Gun Port Build in Final Mate

4.4 Cognition Corporation's Cost Advantage and CostLink-CT

A significant portion of the SAVE Program in the Phase II Interim Cycle was development of cost models and the actual cost data supporting the manufacture and assembly of the baseline F-22 gunport design. The basic premise for the cost models, was that costs should be activity based and feature driven through parametric definitions extracted from the engineering model. The parametric definitions populate Cost Advantage cost model(s), by way of Costlink-CT, where the manufacturing process is defined and cost is derived from the production activities and material usage. Cost Advantage, a commercial knowledge-based costing tool, was used to analyze the feature based cost data. The cost drivers associated with different design variations and how those changes might impact manufacturing processes could then be viewed. Within the cost model, considerations were made for non-recurring tooling, learning curves, realization, labor rates and various burden rates (e.g., overhead).

A feature-based Numerical Control (NC) machining model was developed first. The NC machining model was defined based as CATIA exact solid features such as: fillets, holes, and pockets. Upon completion of the NC machining model, data requirements and cost model formats were developed for composite and an assembly model cost models. Composite part data was gathered and CER's (Cost Estimating Relationships) pertinent to costing composite parts, based on part geometry, and any related process specifications were developed. Consistent CER's for composite parts were successfully developed and used to populate the Cost Advantage composite part model. Likewise, development of an assembly cost model was successful and populated with required data.

An integral component of the cost analysis was the ability to populate those cost models with required data from the CAD model. To enable this population, Costlink-CT was used. Costlink-CT 2.0 is the integration module that closely connected Cognition's Cost Advantage to Dassault Systeme's CATIA solid modeling system. This link allows users to access Cost Advantage's costing and manufacturability functions from within the CATIA environment. Costlink-CT provided a means for designers to get immediate feedback on the cost and producibility of parts modeled with the CATIA solids modeler.

The link works within a CATIA session. Costlink-CT accesses the part model information through the CATIA Application Programming Interface. Costlink-CT provided as a series of FUNCTION load modules appropriately executed by the Costlink user interface. The user interface is implemented as a CATIA Graphics Interactive Interface (GII) Function. Costlink-CT function commands allowed users to access Cost Advantage functions from within the CATIA environment. Users were able to create new cost notes, save and restore cost notes, and update cost notes with new part information extracted from CATIA models. The cost notes were generated for the active CATIA part model. Also, facilities were provided for the user to highlight features in the CATIA part model from Cost Advantage.

Information extracted consists of part material information (mass properties), part process information, features and their parameters and user added data which included dimensions, attributes and tolerances. The extracted part information was mapped into process specific terms (e.g., terms applicable to machining, casting, etc.), and then transmitted to the Cost Advantage software for manufacturability/cost analysis. Costlink-CT provided an open interface that could translate the extracted data to support any user-developed Cost Advantage process model, based on user defined mapping of CATIA model data to process model data. Changes to the part model within CATIA are sent to the Cost Advantage cost note the next time the note is updated through Costlink-CT. However, edits to the cost note within Cost Advantage are independent of and do not affect the CATIA model. User interaction was mechanized through the Costlink-CT Function palette, CATIA session dialog zone, prompt windows and the CATIA menu bar and toolbar. Costlink-CT has no independent user interface of its own. User interaction was limited through the CATIA application.

The following part was used in the Interim Demonstration for the second phase of SAVE. A F-22 composite skin cover was used for the demonstration of the Costlink functionality. The part and its feature definition is illustrated in Figure 5-10 below.

The CostLink functionality was used to extract the process characteristics and features and to perform a cost assessment of the part. The resulting cost sessions are illustrated in Figures 5-11 and 5-12 below.

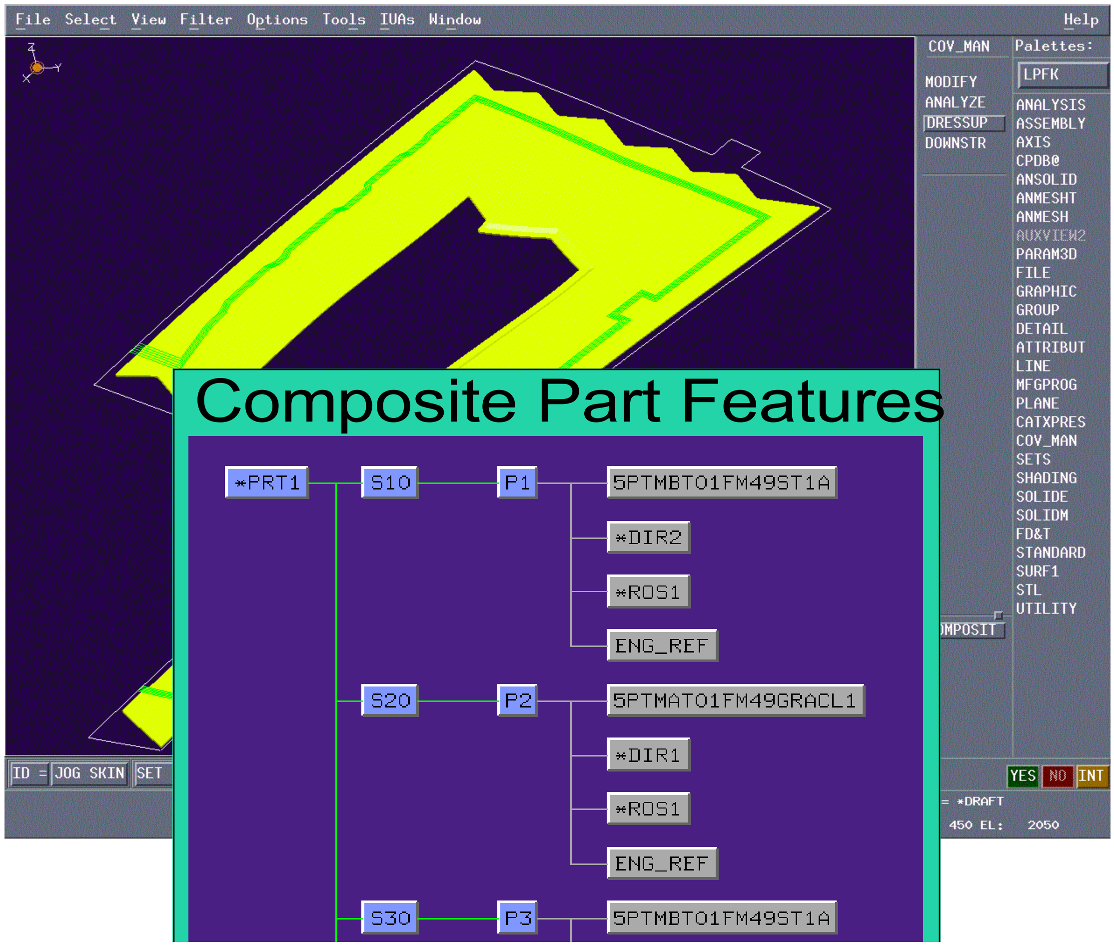


Figure 5-10. F-22 Composite Skin Cover Detail

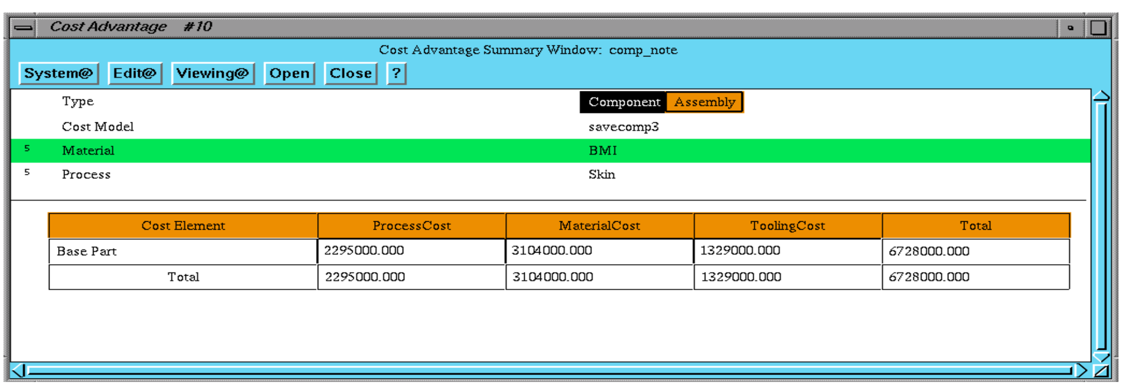


Figure 5-11. Summary Cost of the Part in Cost Advantage

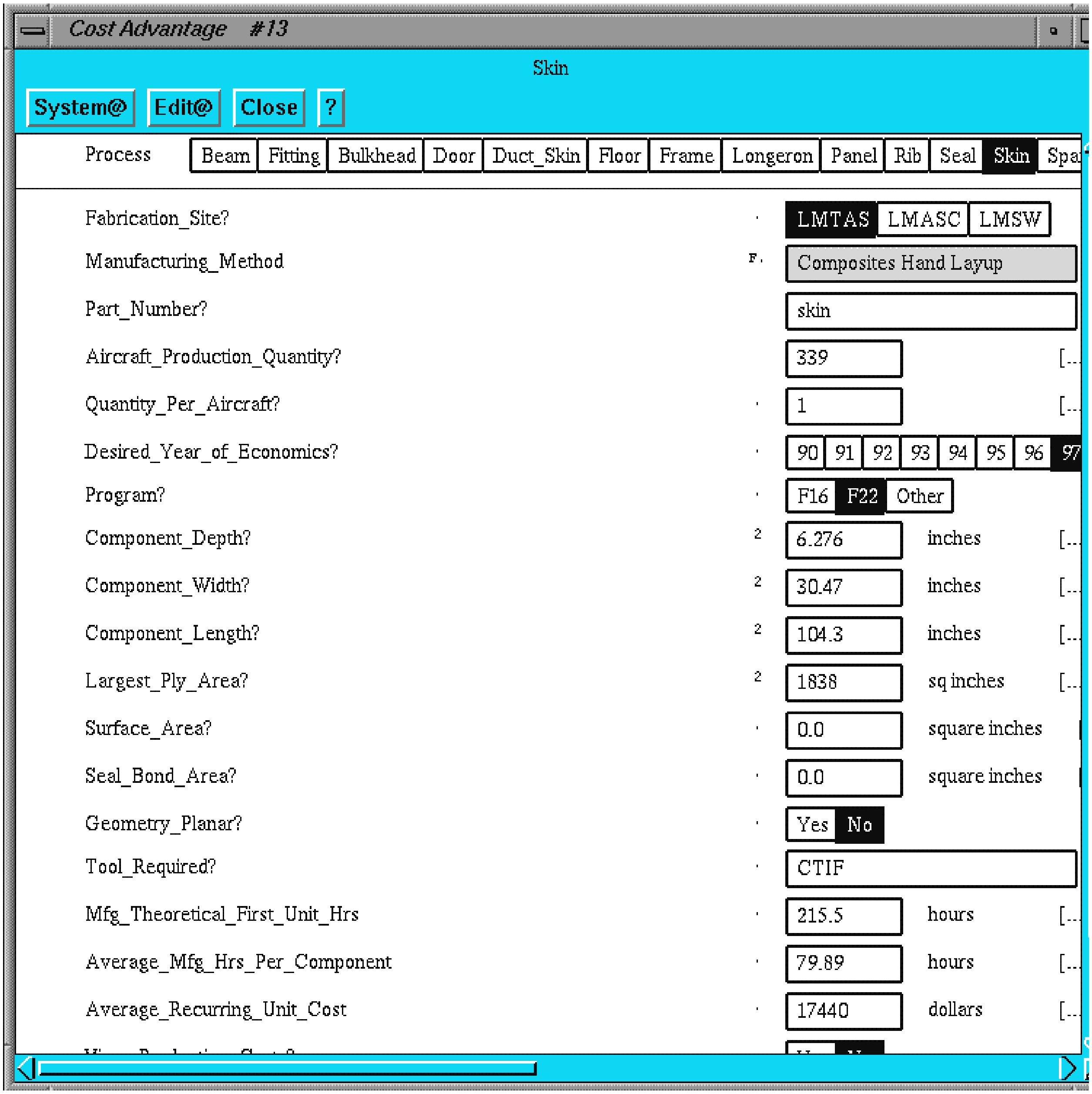


Figure 5-12. Process Characteristics Extracted and Processed

4.5 Engineering Animation Incorporated's VSA-3D

Engineering Animation Incorporated (EAI) provided a CAD integrated software tool which performed statistical analysis to determine the risk of achieving dimensional assembly objectives based on a chain of geometric features which are variationally bound by fabrication specification limits. VSA-3D was chosen due to its ability to read the CATIA FD&T (functional dimensioning & tolerancing) annotations.

VSA-3D analyses required CATIA Exact Solid (solide) model definition, with appended FD&T annotations. The model preparation also required proper definition of assembly features influencing the method of assembly, and measurement operations. The VSA-3D provided user interfaces to enter feature relationships which define operations of assembly between parts, and which define measurement operations between critical points of interests. After defining assembly and measurement operations, the user must Organize the models in the CATIA session into an assembly process plan (i.e., a sequence). The process plan forms a structure for attaching assembly and measurement operations. The simulation will enable the user to determine the level of risk existing at each measurement within the assembly process.

EAI provided customized clients, which would read and write data to the "operation level" of the SAVE data model. The SAVE utility is process plan based; each process plan containing numerous operations. If multiple measurement operations existed at an operation level, the VSA-3D client would rank the risk parameters and report the highest risk measurement output to the SAVE risk summary tool. The SAVE data model does not manage to geometric-feature level at this time.

EAI provided two clients for demonstrating the transfer of data to the SAVE database. The clients are as follows:

- **pop_vsa: –** Used to populate ranked VSA-3D simulation output parameters to the risk object area of the SAVE database. The parameters were integrated to the operation level based on relating VSA-3D measurement operation names to the process plan operation names.

- **read_vsa: –** Used to simply read back VSA-3D information populated to Operations within the SAVE database.

4.6 Science Applications International Corporation's ASURE

ASURE is a decision support tool that enables a designer to perform risk based trade studies to support design decisions. Use of this tool within the SAVE environment provides a designer with the ability to access the data model and pull existing information into the risk model, thereby avoiding reentry tasks and enabling the use of the most recent data. While the SAVE data model contains a variety of information that could be utilized by ASURE, the version of ASURE that was used in the Interim Demonstration only allowed the import and export of the process plan and risk object information associated with each process.

In the Phase II Interim Demonstration, ASURE was used to illustrate:

1. The manner in which ASURE provides a designer with a quantitative method to aid in the decision making process

2. How ASURE helps a designer avoid the time consuming task of building the process plan portion of the risk model by enabling a designer to link to the data model and extract a process plan.

Two issues were identified that would represent a trade-study where risk could be evaluated. The issues were:

1. Selection of manufacturing methods
2. Selection of material for the insert.

The material selection trade study originally involved the choice between stainless steel and Inconel for the skin insert (Figure 5-13). Later in the design effort, the material choices were changed to stainless steel (17-4PH) and titanium (TI-6-4). Since sufficient information was available for this trade, the material trade was selected to demonstrate the utilization of ASURE within the SAVE development environment.

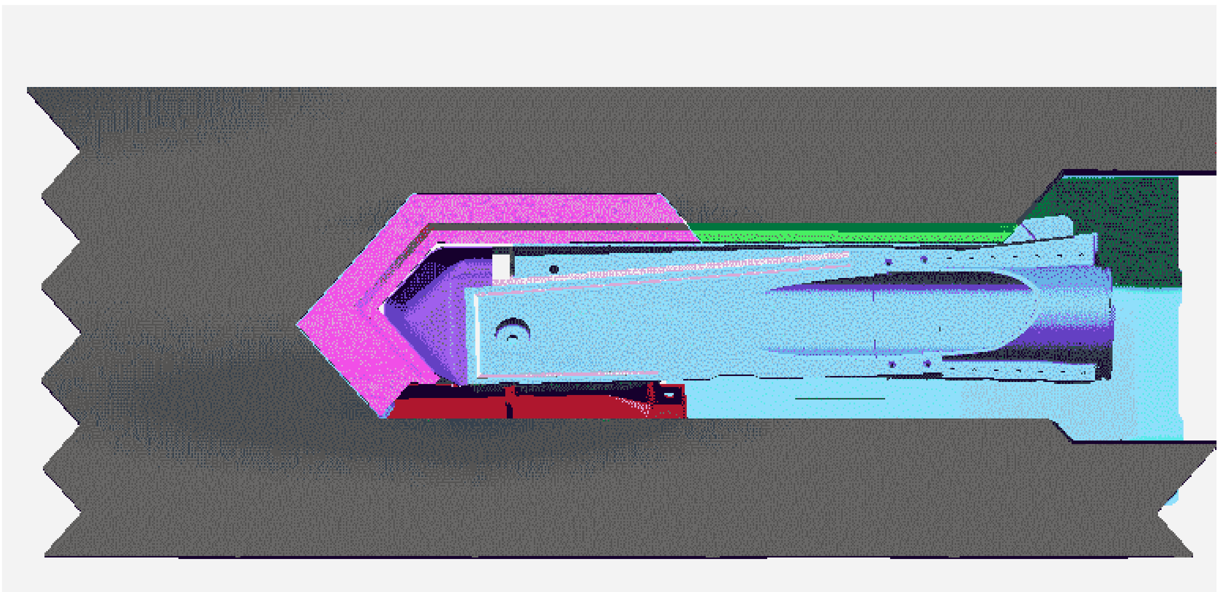


Figure 5-13. Skin Insert

In the absence of any known or perceived risk associated with the use of either alloy, a decision was made to utilize the process plan to develop a risk model that could predict the likelihood of manufacturing a defect free insert when machining each alloy. The resulting model incorporated a "stack-up" of risks for each machining operation to enable the evaluation of the risk associated with generating defects throughout the sequence of operations. This model provided the potential to identify operations that were "risk drivers" for the manufacturing process.

Having defined the application of risk assessment, several assumptions were made by the risk analysts based on the information acquired from the designers and manufacturing experts. The key assumptions were as follows:

- Process plans for stainless and titanium are identical.
- Standard tools are used in manufacturing insert.
- Set-up represents a nominal opportunity for defects.

- Probability of a defect is based on operation, not number of times operation is performed, e.g., drilling of 50 holes vs. 50 occurrences of drilling.

- Machine shop is experienced in machining titanium.

- Manufacturing experts prediction of potential for defect is acceptable in the absence of statistical process control data.

In an effort to minimize the effects of "noise," only key manufacturing operations are incorporated into the model, e.g., only those operations that are judged, by manufacturing experts, to represent a reasonable potential for defect generation.

Having decided on the aggregation approach to analyzing the process plan for each material, the manufacturing experts identified key operations, i.e., those that would likely result in defects, such as, milling, finishing, deburring, drilling, reaming, painting and rubber stamping (Figure 5-14). After generating a model that included the key operations, the likelihood of generating a defect for each operation was acquired from our manufacturing experts and the data was entered into the titanium and stainless models. The use of SAVE was beneficial in this step for importing the hierarchical process plan structure and data into ASURE. The use of SAVE avoids debugging time due to typographical, as well as model creation time. Additionally, the

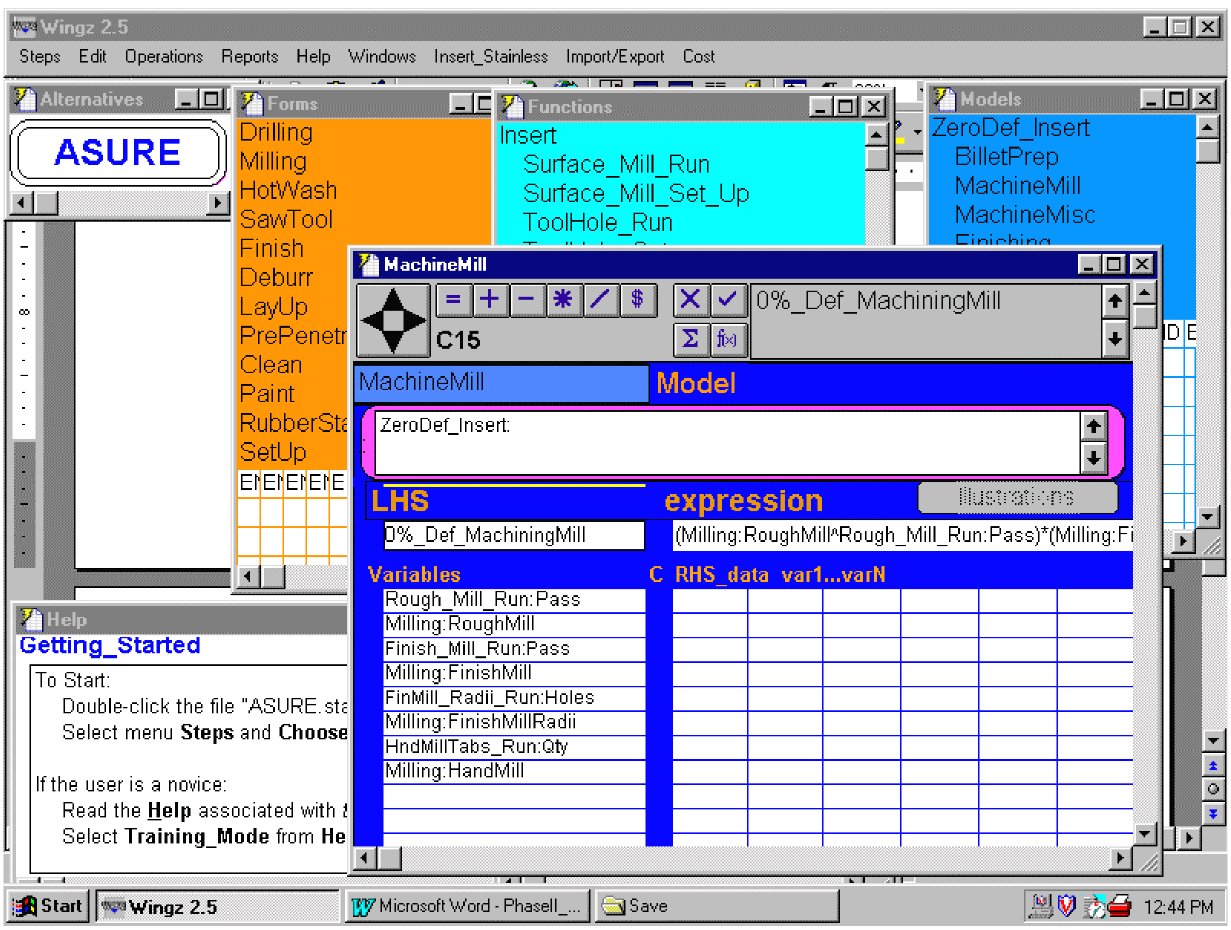


Figure 5-14. Key Milling Operations

availability of the process plan information enables a designer to "cut & paste" the information into the models that drive the simulations. This too avoids debugging time associated with typographical errors.

After creating the two models, each model was run to generate expected defect rates for each material. These results were compared to determine whether the risk for any one material was significant when compared to the other material. A summary of the results were as follows:

- For a machine shop that is experienced in stainless and titanium, there is a nominal difference in the risk associated with either material.

- As an example, if we are interested in what we would expect 90% of the time, we can see from Figure 5-15, that we predict 95% or less acceptable parts for titanium and 97% or less for stainless.

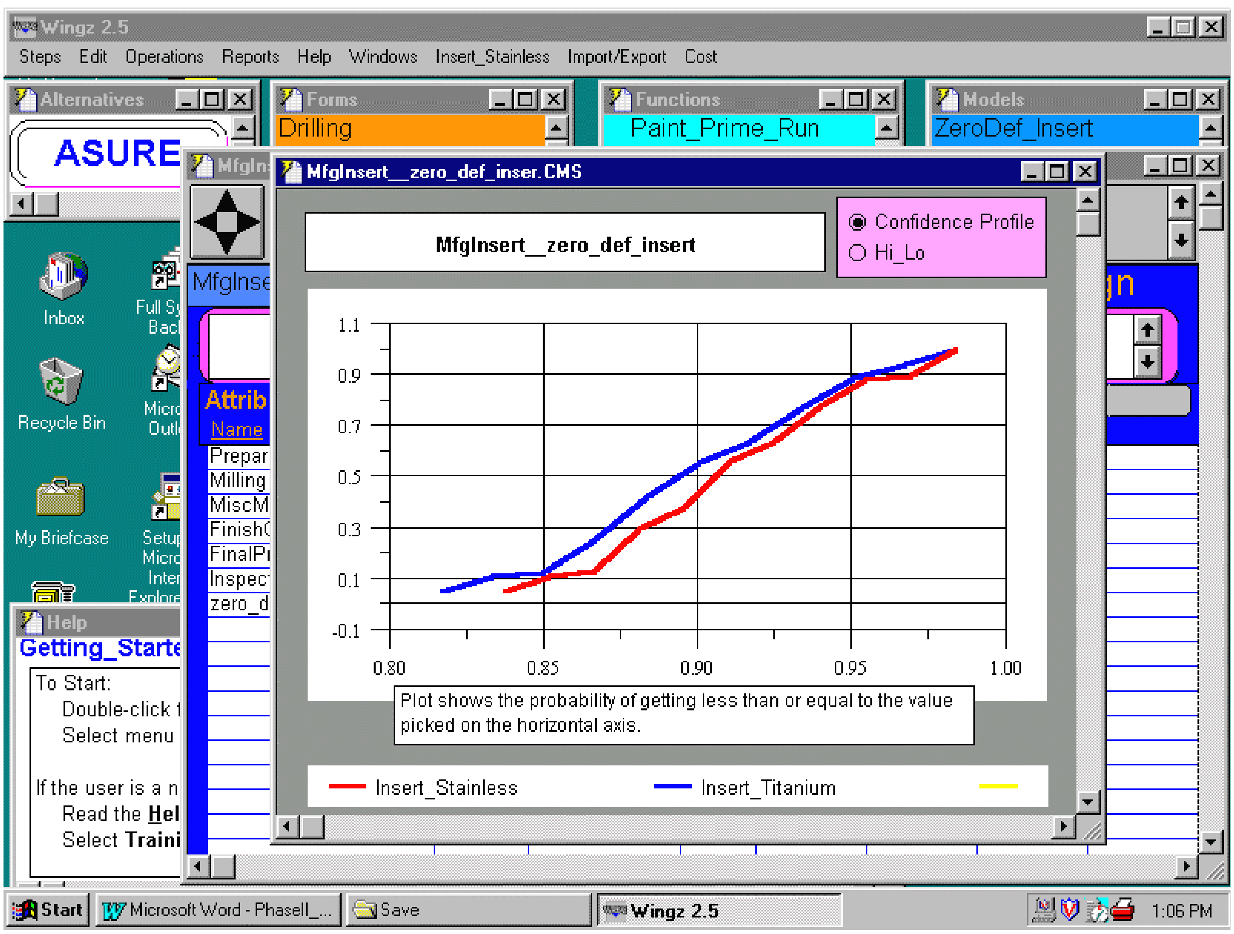


Figure 5-15. Comparison of Stainless vs. Titanium

Having ensured that, for a machine shop experienced in machining the materials, the risk associated with manufacturing the insert out of titanium vs. stainless is nominal. The designer was able to eliminate the producibility risk issue and focus on other issues that affect the material selection decision. As an example, issues included:

- Is an experienced machine shop available?
- What is the cost associated with each design?
- Does the design and machining requirements support the use of standard, off the shelf, billets?
- What is the lead-time associated with procuring TI-6-4 vs. 17-4PH? E.g., between 12 and 20 weeks for stainless and an additional 10weeks to acquire Titanium.

Additionally, ASURE has an export function that enables a designer to populate the SAVE database with a process plan. While not utilized in the Phase II Demonstrations, this functionality is beneficial when a designer elected to alter a process plan based on operations that represent "risk drivers." Finally, future potential for savings involves the ability for ASURE to access legacy databases and import SPC data. The ability to utilize existing SPC data in risk assessment models represents an opportunity to incorporate known capability as opposed to manufacturing experience based estimations.

4.7 Workflow Manager

The first version of the SAVE Workflow Manager (WFM) was completed shortly before the Interim Demonstration, and was not used throughout the design exercise. Most simulation tools were interfaced to the WFM and tested prior to the demonstration. This effort identified several improvements to the WFM which were incorporated during the final cycle of development. The key enhancement was extending the workflow model to support emailing tool users in the case of interactive tools which must have a user present when the tool is launched.

5.0 Metrics

A detailed metrics plan was developed for the Phase II Interim Demonstration, which provided the foundation for the Metrics Plan documented in the SAVE Software User's Manual. This plan clearly identified the approach and difficulties of metrics validation using a design problem tied to an on-going aircraft program. The major problem posed is that validation data may not be available for some time as the identified manufacturing processes can take some time before reaching the shop floor. This is particularly true during the pre-production phase of an aircraft program, when production rates are quite low.

Chapter 6

Phase II Final Demonstration

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 Goals

As the last of the three SAVE demonstrations, the final demonstration was of vital importance to the overall success of the program. The underlying goals of the activity were twofold. The first involved testing the infrastructure and integration approach by using the environment to conduct a series of design studies. By using the environment in this way, the demonstration team provided valuable feedback for use by the commercializing vendors. The second, and more important goal, was to assess the benefits of applying the integrated virtual manufacturing environment during product development. This demonstration concentrated specifically on quantifying the benefits of the integration, not the simulation tools themselves.

The demonstration team provided a great deal of useful feedback about the use of SAVE itself. This information is documented in detail in the SAVE Computer Software End Item document. Section 5.0 of this Chapter contains a summary of the findings relative to the integration benefits.

2.0 Candidate Selection Criteria

The demonstration team worked with various Integrated Product Teams (IPT) within the F-22 program to identify potential assembly and detail part trade studies that could be used as the basis for the SAVE final demonstration activity. Criteria for selecting the problem were developed in order to facilitate selection of a study that would allow SAVE to be used to its fullest capability. These criteria are as follows:

- Problem must contain a structural assembly in order to demonstrate the capabilities of all tools within the suite.
- Assembly and/or its parts must be suitable for cost analysis with the available knowledge bases.
- Activity must be an upcoming program redesign effort or trade study in order to allow SAVE to provide useful and timely feedback to an existing aircraft program.

Several candidates were evaluated by the SAVE demonstration team and the F-22 IPTs with the F-22 main weapons bay door installation selected for the Final Demonstration. Details of the study are discussed in Section 3.0.

3.0 Trade Studies / Demonstration Scenario

The SAVE final demonstration focused on an actual problem that was being addressed by the F-22 program. The SAVE team worked the problem in parallel with the F-22 IPT, using the SAVE Virtual Manufacturing Environment and providing feedback to the F-22 program where possible.

The study centers on the F-22 main weapons bay (MWB) doors and their installation onto the aircraft. Experiences with the installation of the first three doors showed that the doors were not meeting engineering mismatch tolerance requirements when installed on the aircraft. The solution to this problem is compounded by the fact that the doors and midbody are built at LMTAS in Fort Worth, Texas, while they are installed months later at LMAS in Marietta, Georgia. Under current schedules, four to six more midbodies are manufactured and shipped before the first doors are installed on the aircraft. This schedule results in a lag time for feedback on installation problems as well as any potential solutions.

In this area of the aircraft, there are several fixed and moving surfaces coming together. Figure 6-1 shows the main weapons bay door area and points to the parts that are involved in the mismatch. There is one long, fixed skin that runs the length of the main weapons bay. There are three doors in the installation. Although the fit problems are present with two of the three doors, the auxiliary seal door with its close proximity to the fixed skin seems to experience the most fit-related issues. The primary areas of interference and mismatch are highlighted in Figure 6-2.

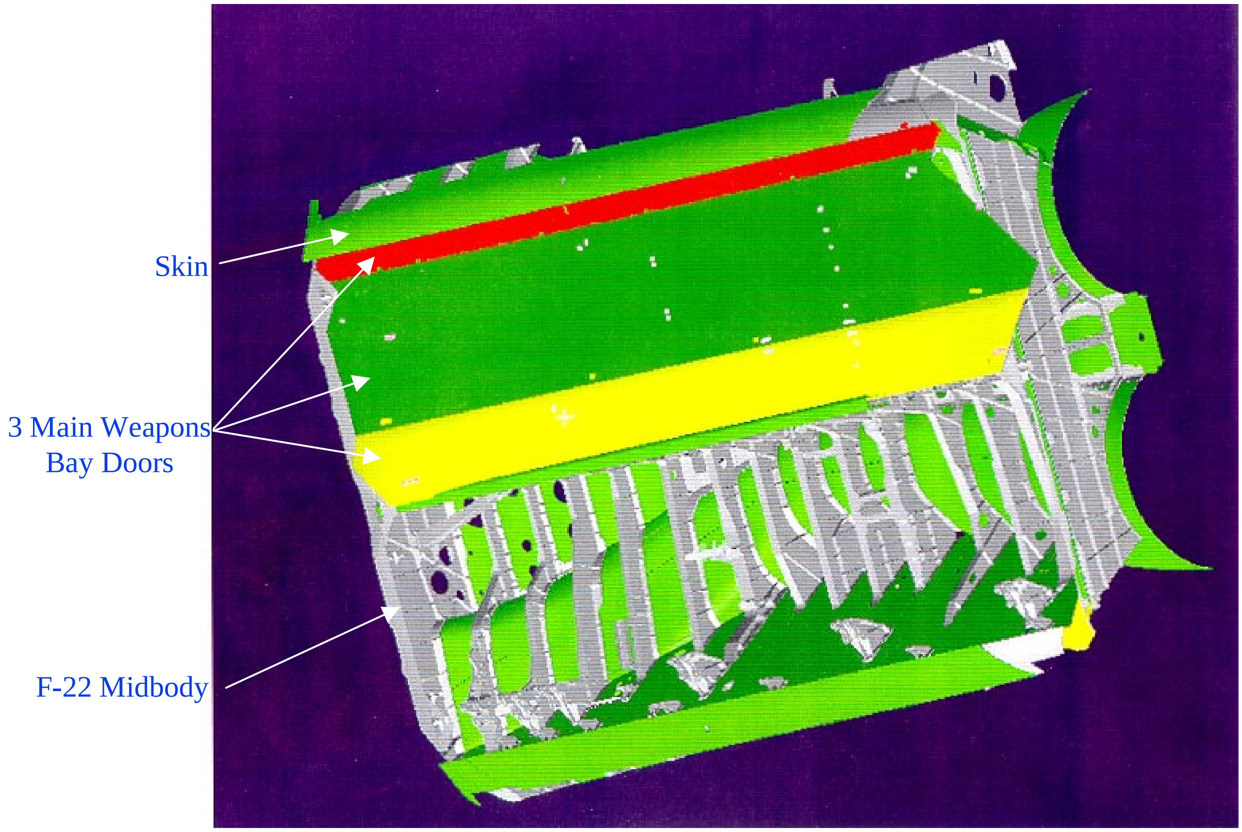


Figure 6-1. F-22 Midbody with Main Weapons Bay Doors

In evaluating the MWB door fit issues, the F-22 structures IPT identified several possible contributors. The first contributor related to the overall tooling philosophy employed for locating the door hinges and surrounding skins. An Inner Mold Line (IML) tooling concept was originally selected by the program because of its inherent cost benefits. This concept controlled and located parts to the IML of the aircraft, allowing the Outer Mold Line (OML) to float. Unfortunately, the tolerance buildup and part positioning obtained with the IML concept caused the improper fit between the doors and the midbody. The second contributor centered on the fact that the MWB doors are never installed into the bay prior to their shipment. Fit problems are not identified until the doors are installed months later at another facility. Feedback from this

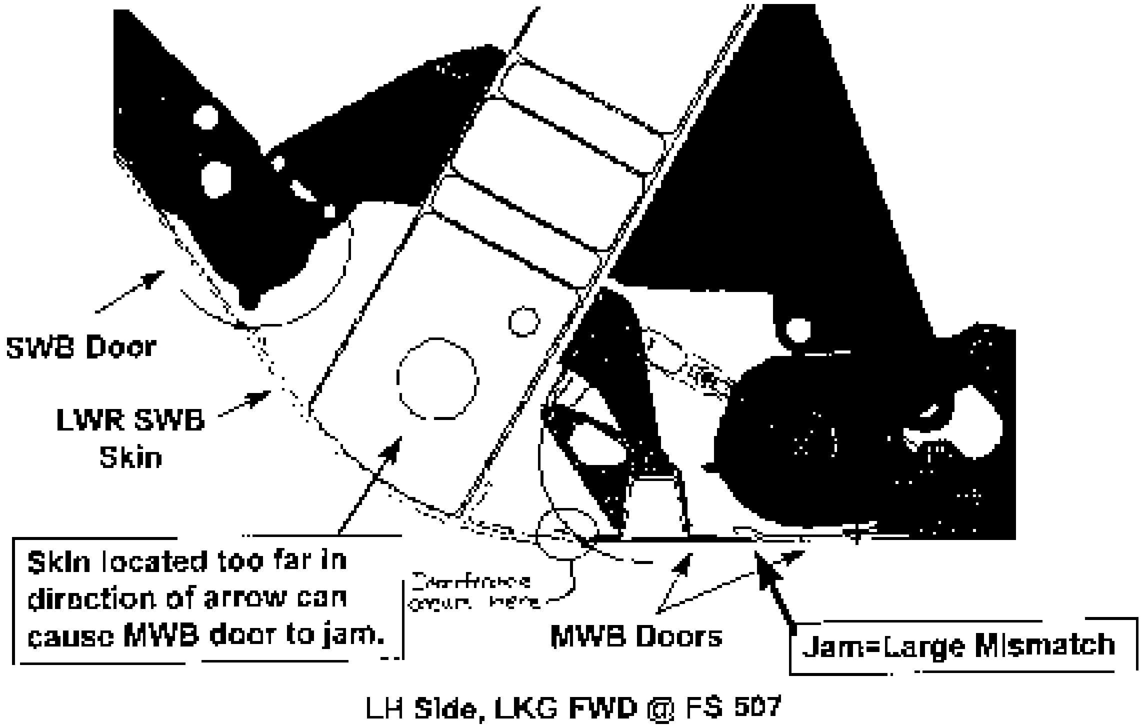


Figure 6-2. MWB Door Interference and Mismatch Areas

installation process is not received until after several additional midbodies have been produced and shipped.

To address these primary contributors, the F-22 program identified and evaluated potential tooling and process changes. As a part of the demonstration, the SAVE team used the integrated virtual manufacturing environment to evaluate these options, thus providing additional information to the F-22 program in their decision-making process.

Figure 6-3 shows the flow within the SAVE demonstration activity. Two trade studies were conducted. The first study evaluated the effect of changing from an IML to an OML tooling philosophy. Holding the outer mold line of the vehicle should provide a more accurate location for the skin and hinges and, therefore, increase the probability of a successful fit between the skin and doors. The second study addressed the addition of a fit check process at LMTAS prior to midbody shipment. By incorporating a fit check, any problems with interference or mismatch would be identified earlier and allow time for problem resolution prior to the manufacture of additional midbodies.

The SAVE team conducted the trade studies with five primary goals in mind.

- Reduce door installation time.
- Eliminate mismatch problems.
- Achieve a repeatable MWB door installation process.
- Accomplish goals with minimal impact to overall costs.
- Validate results through integrated simulation.

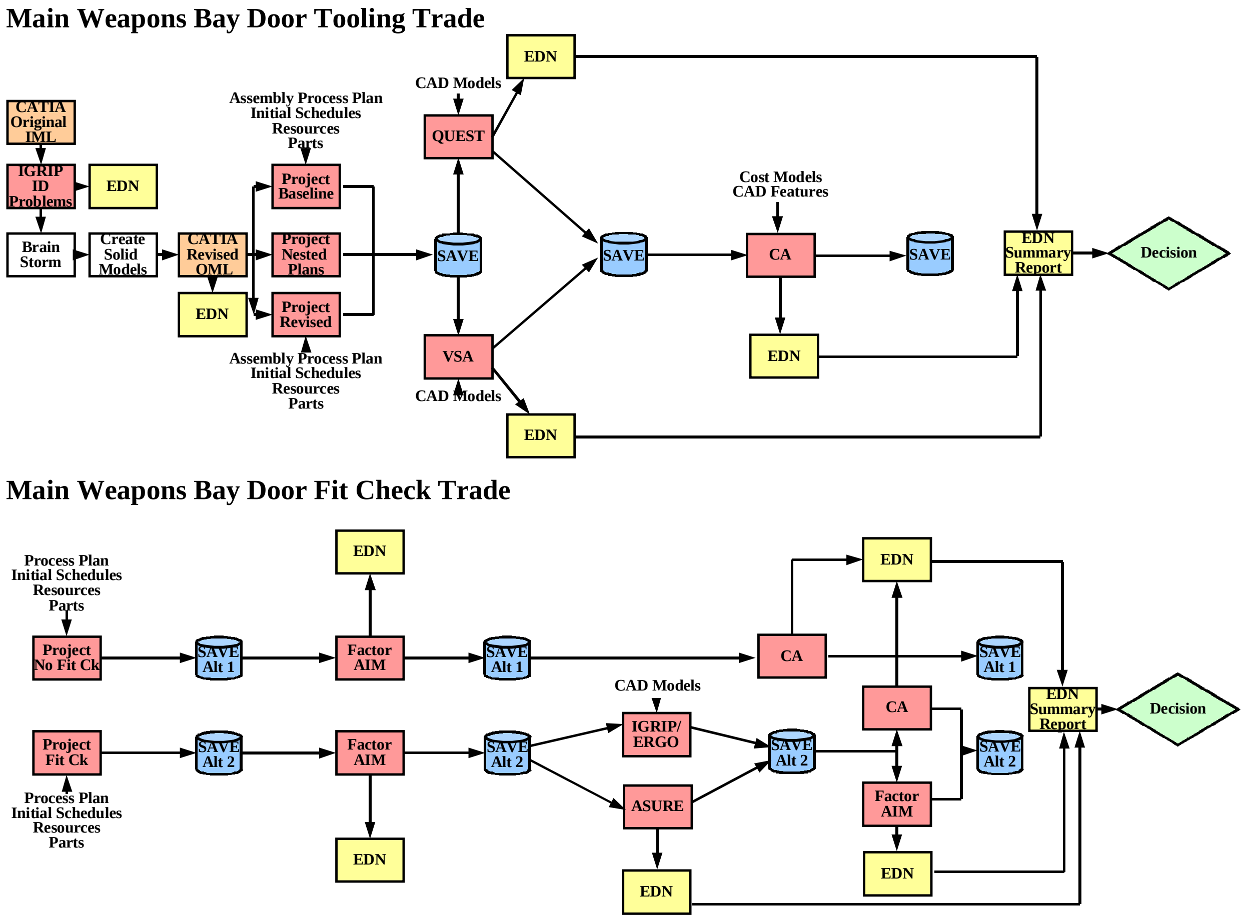


Figure 6-3. SAVE Demonstration Flow

4.0 Tool Usage

The integrated manufacturing simulation tools within the SAVE environment were used to evaluate the process and tooling changes in the trade studies. The **Work Flow Manager** (WFM) provided a mechanism to organize the studies, including the tool execution order and data flows/tool dependencies. Figure 6-4 shows the workflow for the MWB Door Tooling Trade.

The team used **Deneb Robotics' IGRIP**, an assembly simulation tool, to visualize the changes being made as part of these studies. The simulation showed the three midbody modules moving from their stations to the mate fixture. From there, the mated midbody moved to the bore fixture, where the tooling changes were implemented. Figure 6-5 shows an IGRIP screen shot of the midbody in the bore fixture. Once in the bore fixture, the midbody was located correctly in space relative to the aircraft OML by holding one end fixed while using gauges to properly locate the other end. Once the midbody is assured to be in the correct position, existing tooling details are used to locate and attach the hinges. After the assembly moves to the soft station, shown in Figure 6-6, the skin is attached relative to the hinge locations using new OML tooling. At that point, the fit check is added where the MWB doors are installed and checked for interference or mismatch.

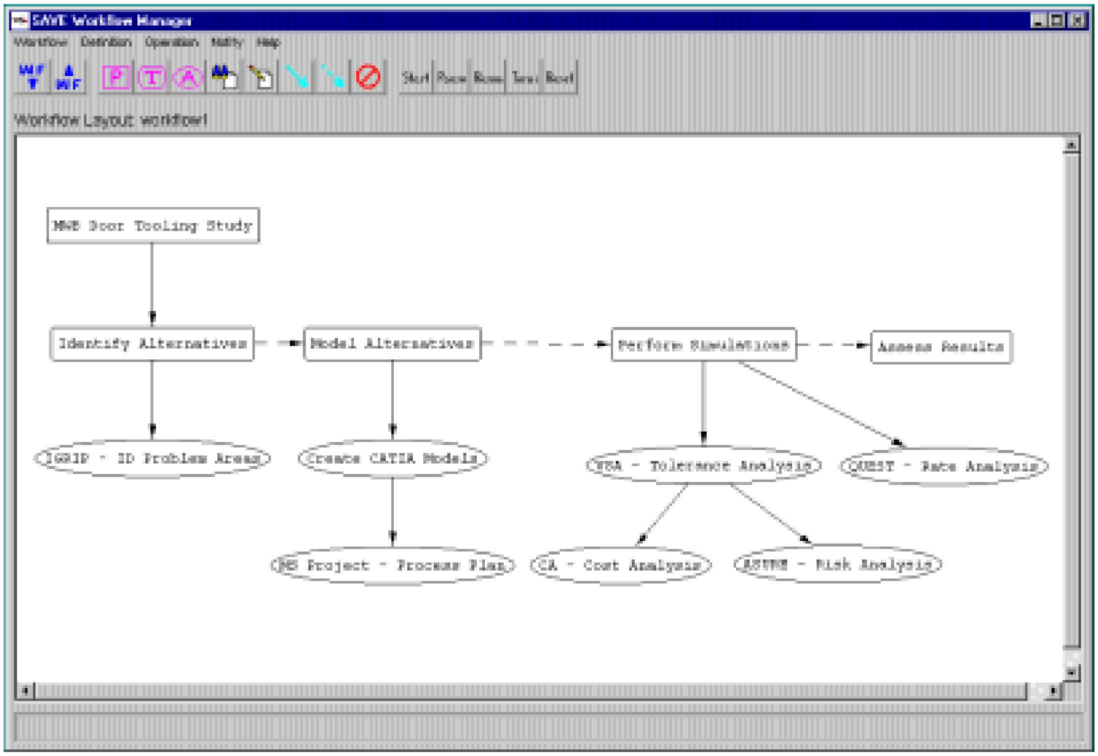


Figure 6-4. Study Workflow

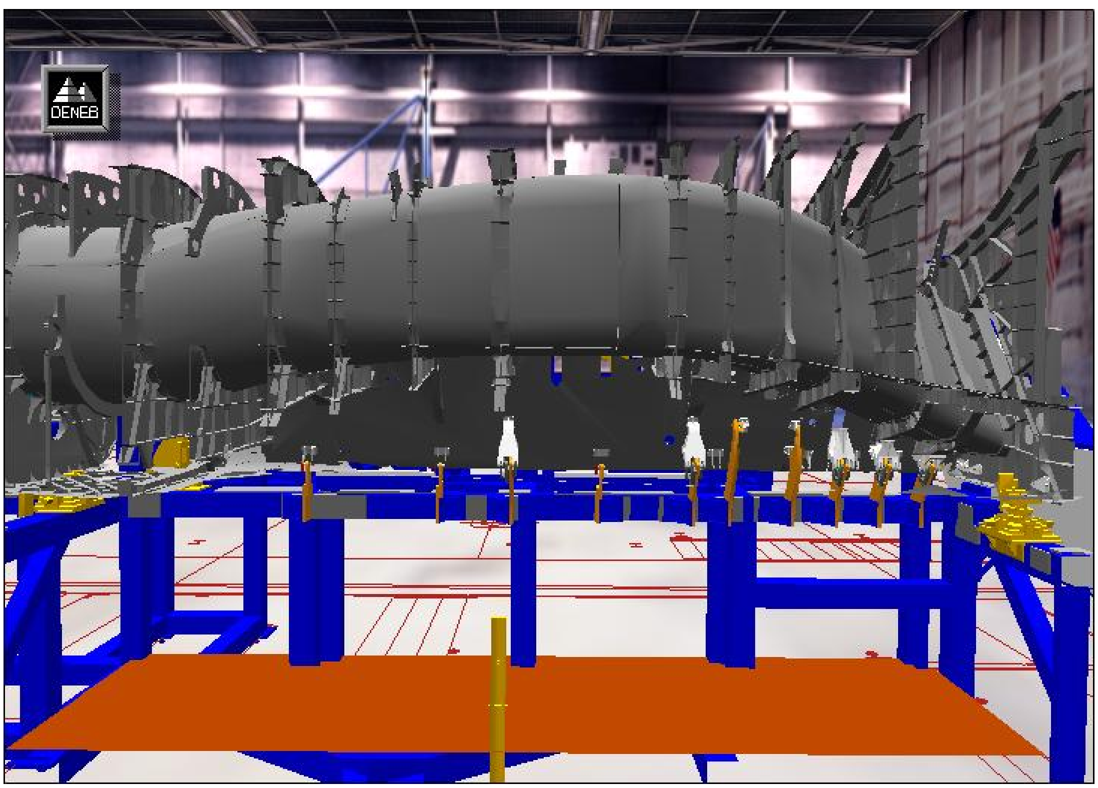


Figure 6-5. F-22 Midbody with Hinges Being Installed

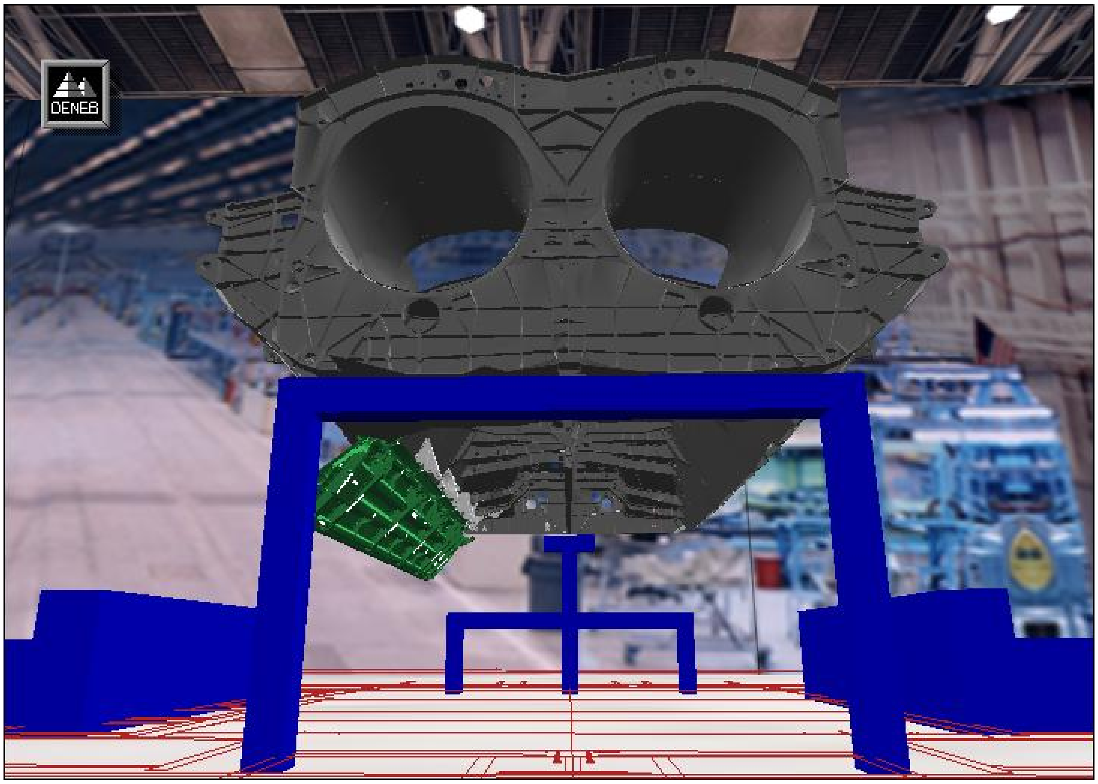


Figure 6-6. F-22 Midbody in Soft Station with Skins Attached and Fit Check Added

4.1 OML versus IML Tooling Trade Study

The OML versus IML Tooling Trade tool usage and data flow is depicted in Figure 6-3. The SAVE tools are highlighted in rose with the arrows indicating data flow to and from the SAVE common database, which is depicted with blue cylinders. The yellow and white boxes reference tools and/or activities that are not directly integrated into the SAVE environment.

The manufacturing engineer (ME) within the IPT typically uses software tools to develop initial process planning data. In the SAVE environment, **Microsoft Project** serves this function. Since Project is the starting point for the trade study, no data is imported from the SAVE environment; however, the tool is wrapped in order to make all of the process planning data available to the downstream simulation tools.

Since this trade study modified an existing F-22 process, the ME extracted the available planning data from the F-22 legacy system and used it as a starting point. The MWB door assembly process plan contains several levels of indenture. Figure 6-7 shows the highest level for this plan including the location and installation of the hinges and skins. Each of these plans expands into its explicit set of operations or job steps. Figure 6-8 shows an expanded plan for one of the four top-level operations. When fully expanded, the MWB door assembly process plan contains over 280 steps. The process plan in Project also contains information about the parts that are consumed and produced at each operation as well as the tooling involved in that operation.

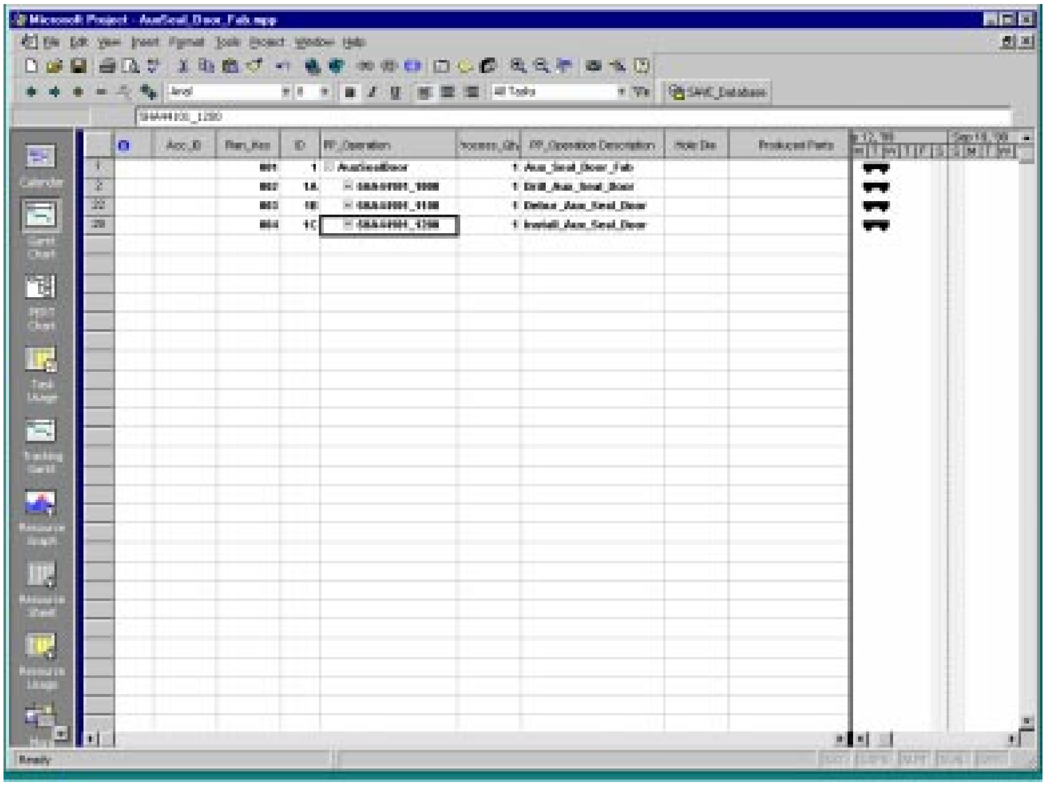
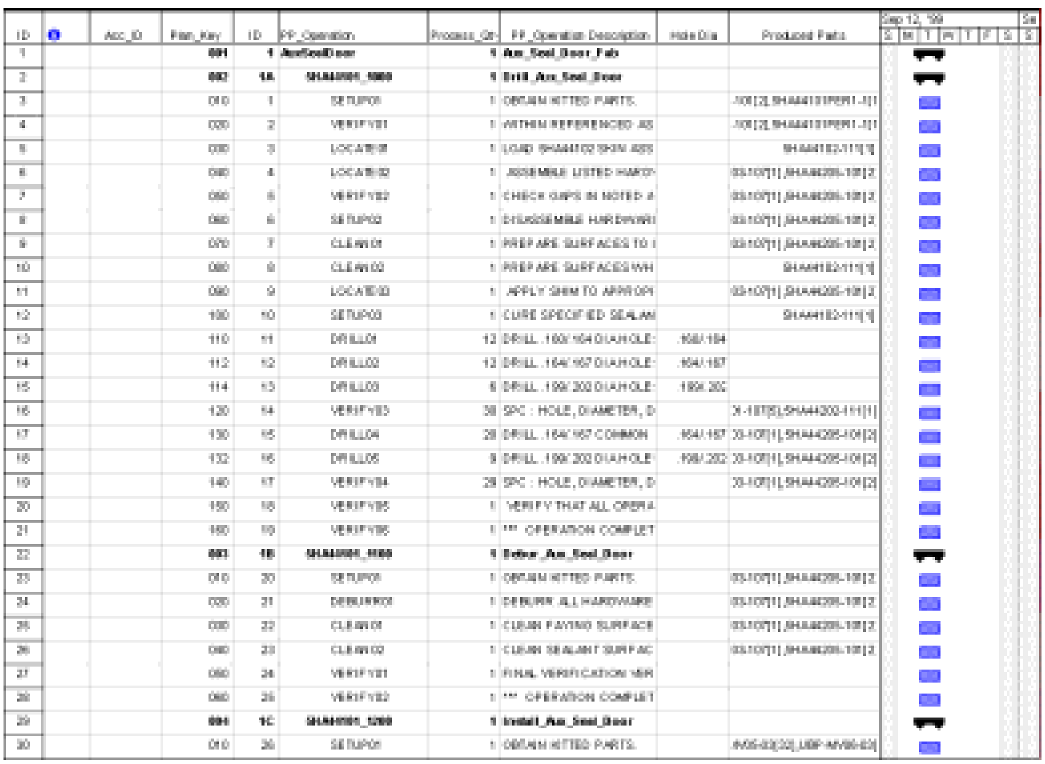


Figure 6-7. MWB Door Top Level Process Plan



ID		Acc_ID	Plan_Key	ID	PP_Operation	Process_Qty	PP_Operation Description	Hole Dia	Produced Parts
1			001	1	AusSealDoor	1	Aus_Seal_Door_Fab		
2			002	1A	SHA44101_1000	1	Drill_Aus_Seal_Door		
3			010	1	SETUP01	1	OBTAIN KITTED PARTS.		-101[2],SHA44101PER1-1[1
4			020	2	VERIFY01	1	WITHIN REFERENCED AS		-101[2],SHA44101PER1-1[1
5			030	3	LOCATE01	1	LOAD SHA44102 SKIN ASS		SHA44102-111[1]
6			040	4	LOCATE02	1	ASSEMBLE LISTED HARD		03-107[1],SHA44205-101[2
7			050	5	VERIFY02	1	CHECK GAPS IN NOTED A		03-107[1],SHA44205-101[2
8			060	6	SETUP02	1	DISASSEMBLE HARDWARE		03-107[1],SHA44205-101[2
9			070	7	CLEAN01	1	PREPARE SURFACES TO		03-107[1],SHA44205-101[2
10			080	8	CLEAN02	1	PREPARE SURFACES WH		SHA44102-111[1]
11			090	9	LOCATE03	1	APPLY SHIM TO APPROPR		03-107[1],SHA44205-101[2
12			100	10	SETUP03	1	CURE SPECIFIED SEALAN		SHA44102-111[1]
13			110	11	DRILL01	12	DRILL .160/.164 DIA HOLE:	.160/.164	
14			112	12	DRILL02	12	DRILL .164/.167 DIA HOLE:	.164/.167	
15			114	13	DRILL03	6	DRILL .199/.202 DIA HOLE:	.199/.202	
16			120	14	VERIFY03	30	SPC : HOLE, DIAMETER, D		3-107[5],SHA44202-111[1]
17			130	15	DRILL04	28	DRILL .164/.167 COMMON	.164/.167	03-107[1],SHA44205-101[2]
18			132	16	DRILL05	9	DRILL .199/.202 DIA HOLE	.199/.202	03-107[1],SHA44205-101[2]
19			140	17	VERIFY04	28	SPC : HOLE, DIAMETER, D		03-107[1],SHA44205-101[2]
20			150	18	VERIFY05	1	VERIFY THAT ALL OPERA		
21			160	19	VERIFY06	1	*** OPERATION COMPLET		
22			003	1B	SHA44101_1100	1	Deburr_Aus_Seal_Door		
23			010	20	SETUP01	1	OBTAIN KITTED PARTS.		03-107[1],SHA44205-101[2
24			020	21	DEBURR01	1	DEBURR ALL HARDWARE		03-107[1],SHA44205-101[2
25			030	22	CLEAN01	1	CLEAN FAYING SURFACE		03-107[1],SHA44205-101[2
26			040	23	CLEAN02	1	CLEAN SEALANT SURFAC		03-107[1],SHA44205-101[2
27			050	24	VERIFY01	1	FINAL VERIFICATION VER		
28			060	25	VERIFY02	1	*** OPERATION COMPLET		
29			004	1C	SHA44101_1200	1	Install_Aus_Seal_Door		
30			010	26	SETUP01	1	OBTAIN KITTED PARTS.		-MV06-03[32],UBP-MV06-03[

Figure 6-8. MWB Door Expanded Process Plan

The indenturing, or nesting, of process planning information is one of the key features available in the SAVE environment. One benefit of this capability is that the simulation tools can use the process planning information at the appropriate level of detail. Some tools, like factory simulation, simulate the process at the macro level while others, like tolerance analysis, simulate the process at a micro level. With SAVE, all of this information exists in one process plan and is useful at any level.

Deneb Robotics' QUEST tool is a highly visual discrete event simulation tool that was used in this study to perform an overall rate tooling analysis for the midbody assembly process. QUEST imported the top-level process plan that summarizes the steps in the assembly process. For each of these steps, or operations, the tooling and part information, including their location on the shop floor, were read from SAVE. In addition, the initial process time estimates developed by the ME and stored via the Project wrapper were imported into QUEST via SAVE.

The QUEST wrapper used this imported information to automatically generate a base model. The analyst started with this base model and added the final logic for the factory level simulation. The ability to import the process, tools and parts from SAVE reduced the time to build the simulation model by approximately 35%. The resultant simulation shows the parts of the midbody moving through the assembly process and identifies an unacceptably high level of tooling utilization for one of the three midbody modules. The factory layout and the potential problem area are identified in Figure 6-9.

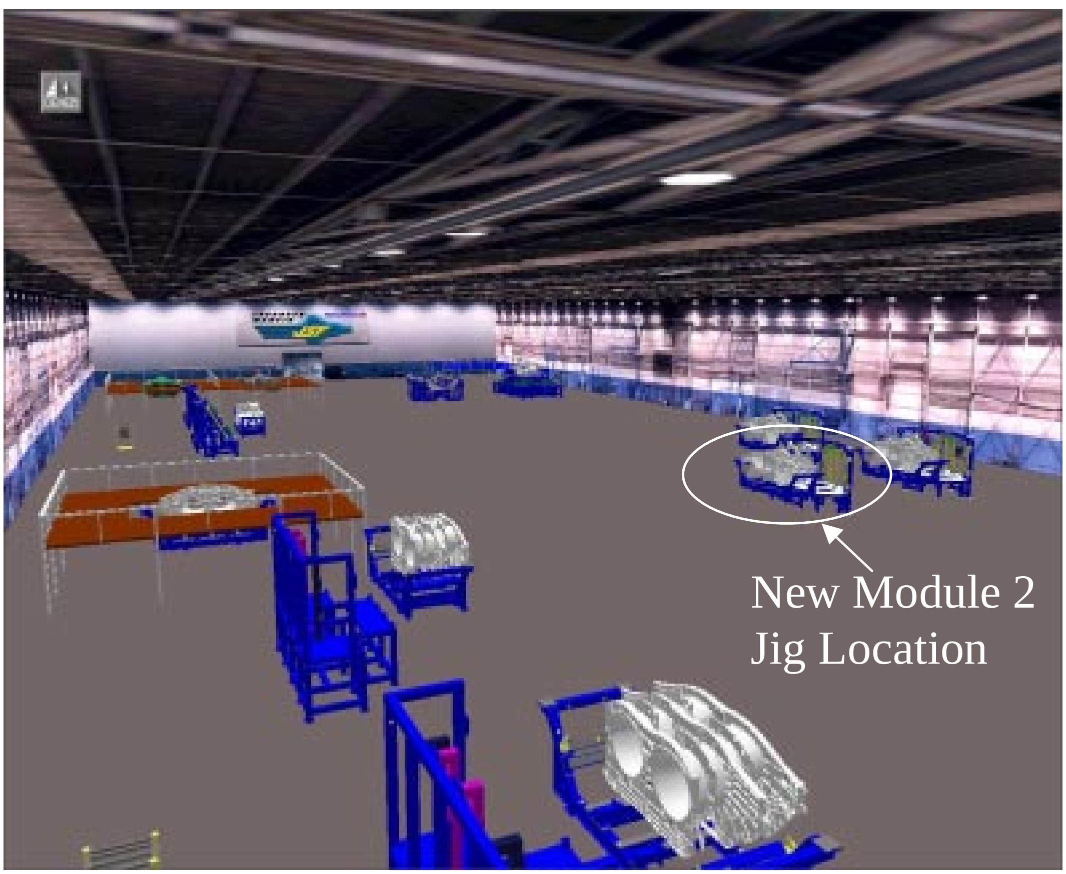


Figure 6-9. QUEST Simulation for F-22 Midbody Assembly

Based on the results of the initial simulation, the SAVE team conducted a trade study which varied span times, number of tools, and crew size to determine the optimum rate tooling solution. Table 6-1 provides the detailed results of this trade. Adding one tool and increasing the span time provides results with little or no risk of tooling over-utilization; however, the F-22 team would have to assess the additional tooling costs and potential schedule impacts against the decrease in risk.

Table 6-1. Rate Tooling Trade Results

Span Between Starts	Tool	Qty	Peak Utilization Percent
43	Module 2	3	75
	Module 3	2	64
	Module 4	3	90
	Mate/BOFX	2	37
	Soft Station	2	91
44	Module 2	3	77
	Module 3	2	62
	Module 4	3	88
	Mate/BOFX	2	33
	Soft Station	2	89
45	Module 2	2	100
	Module 3	2	60
	Module 4	3	86
	Mate/BOFX	2	32
	Soft Station	2	87
48	Module 2	2	94
	Module 3	2	53
	Module 4	3	80
	Mate/BOFX	2	33
	Soft Station	2	81

In order to dive into the details of the mismatch between the auxiliary seal door and the permanent skin, **Engineering Animation's VSA3D** tool was employed to perform a detailed tolerance analysis. The process plan, including the operation sequence and associated parts, for the skin and door installation was read from the SAVE common database. This information was combined with the dimension and tolerance data from the CAD model by the VSA3D wrapper to create a simulation model shown in Figure 6-10. Figure 6-11 shows the model after the parts are assembled and the interference and mismatch contributors were identified.

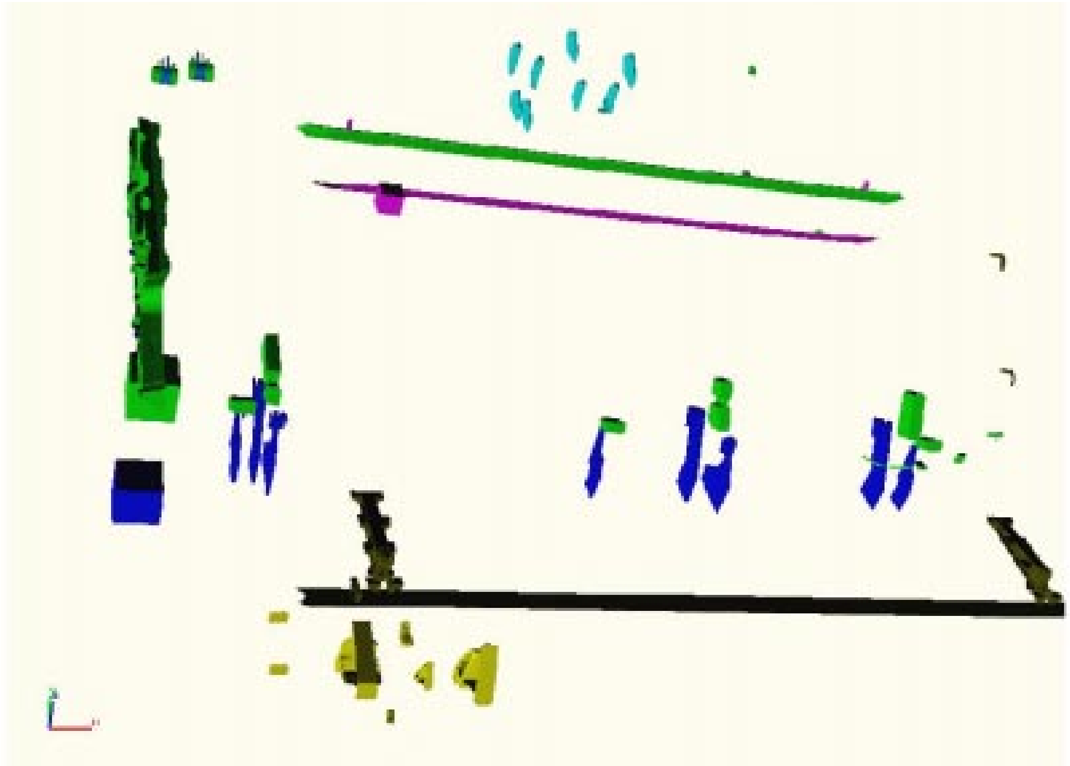


Figure 6-10. VSA3D Assembly Model

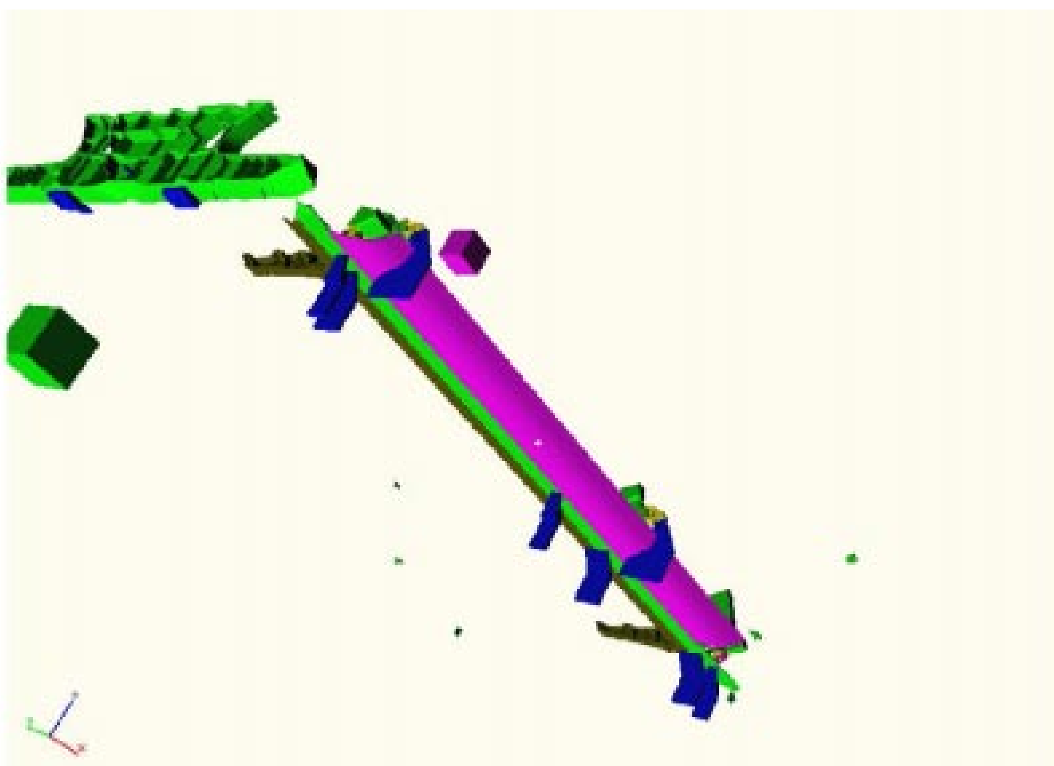


Figure 6-11. Resulting Assembly After Simulation

As a part of the VSA3D analysis, the SAVE team evaluated the proposed OML tooling philosophy to determine the probability of successful installation. The red areas in the histogram in Figure 6-12 show that the door installation was not a 100% repeatable process with the OML change alone. There was still a 7% out-of-spec condition. The tolerance analysis identified two tooling holes as the primary contributors to this condition. Armed with this information, the analyst conducted additional studies to determine if a higher success rate was possible. This analysis showed that modifying the tooling pin diameter eliminated almost all of the out-of-spec conditions. Figure 6-13 shows the results of that analysis that were exported to SAVE.

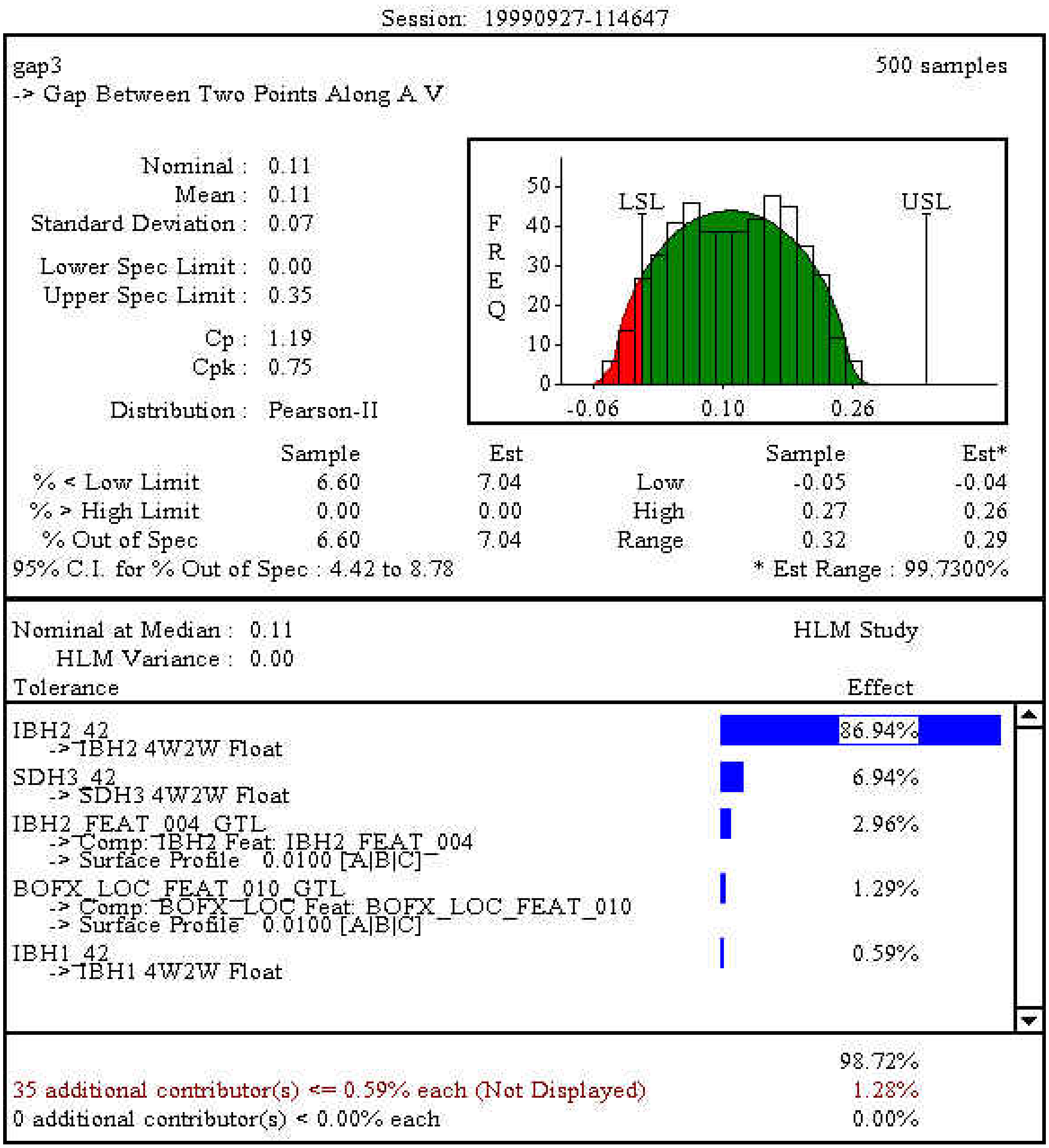


Figure 6-12. Initial Tolerance Analysis

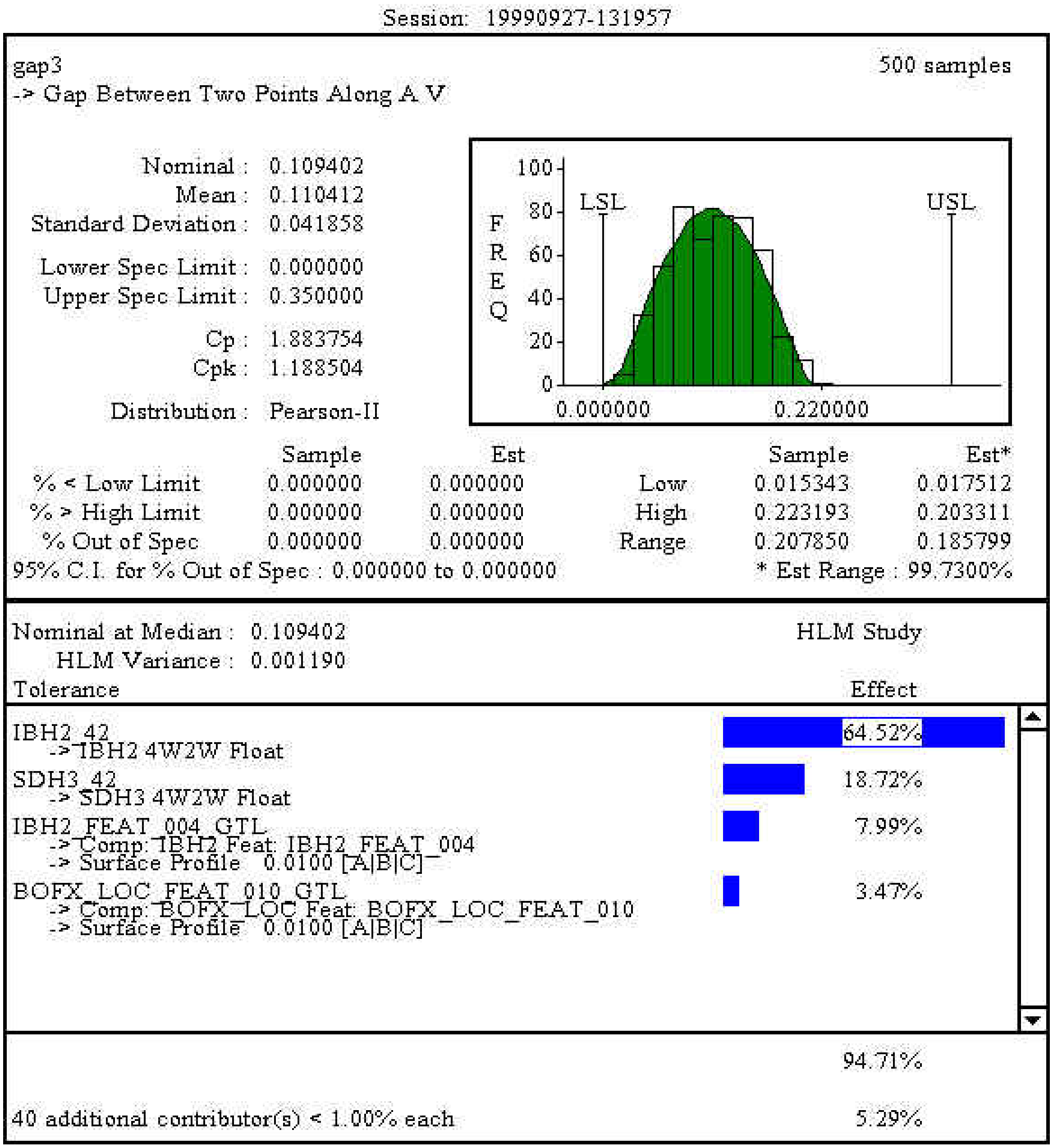


Figure 6-13. Final Tolerance Analysis

Cognition Corporation's Cost Advantage (CA) is a knowledge-based cost assessment tool that enables design-to-cost analysis. In this demonstration, the SAVE team used CA to evaluate the cost of the auxiliary seal door assembly process. This evaluation was selected to allow the team to fully exercise the Assembly Cost Model and the CATIA CostLink, developed as part of the SAVE activity.

This cost estimation tool relies heavily on CAD feature information to make its estimates. Using the CATIA CostLink developed under the SAVE contract, the feature data were interpreted and extracted from the CAD model. Figure 6-14 shows one of the hinges for the auxiliary seal door and highlights some of the features that were extracted using the CostLink. The important features here are the "manufacturing" ones that can include information about the number of holes, hole sizes, material type, and number of parts, etc.

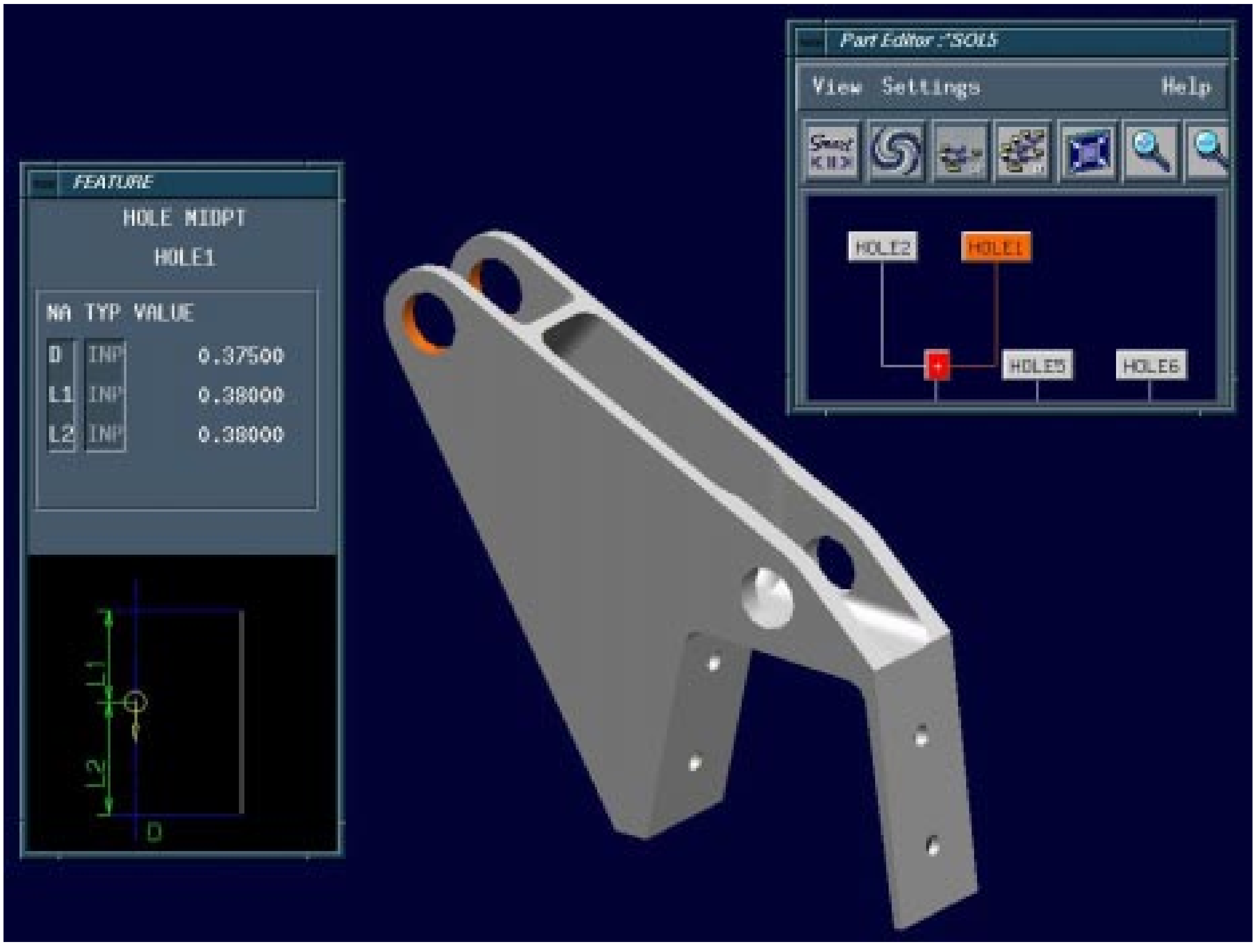
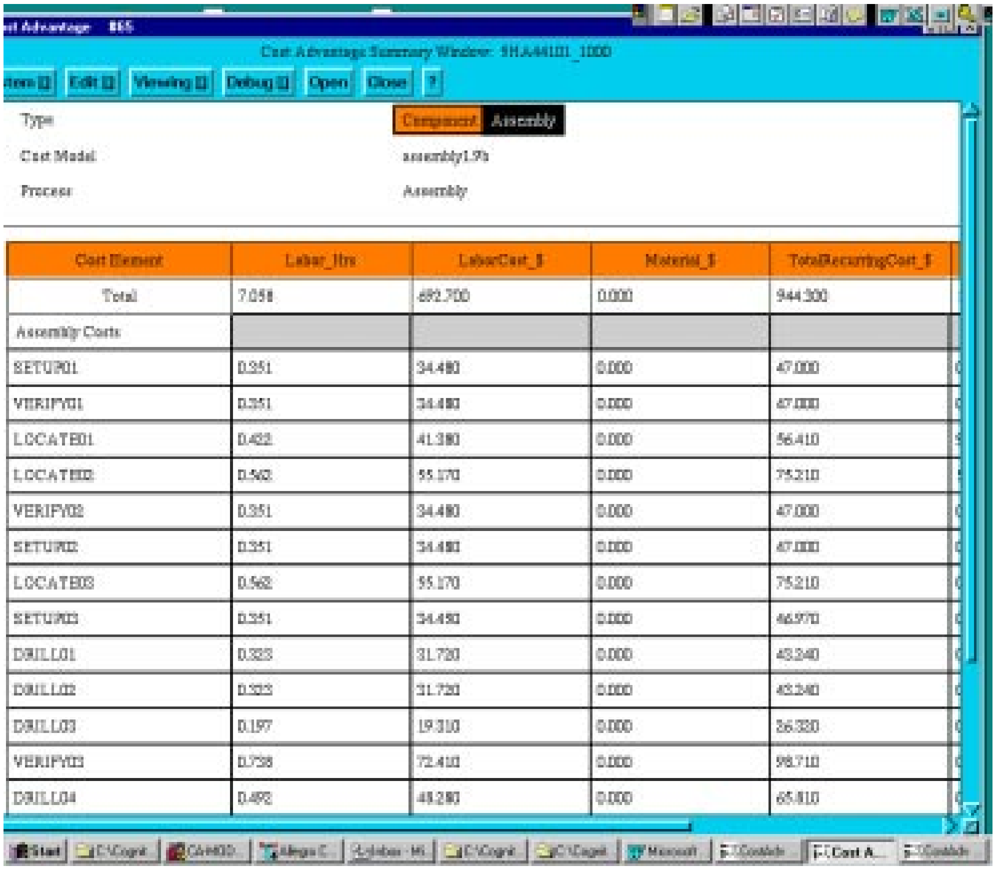


Figure 6-14. Auxiliary Seal Door Hinge Model with Features

Once the feature data was extracted and available, the information was automatically merged with the operations and associated parts that were imported from SAVE. In this plan, there are three levels of indenture each with detailed operations within. Figure 6-15 shows the resulting data for one of the operations in the process. The Assembly Cost Model provided the cost estimating relationships (CERs) as well as standard company data used in those CERs. These two models were used together to conduct a cost analysis, shown in Figure 6-16, for the auxiliary seal door assembly. Cost Advantage provides an overall recurring cost estimate and exports that information to the SAVE database. The automatic model generation and CAD feature extraction resulted in a 50% reduction in the time necessary to conduct the cost analysis.

After assessing the impacts of changing to an OML tooling philosophy using the SAVE Virtual Manufacturing environment, the team used several tools to review and compare the results.

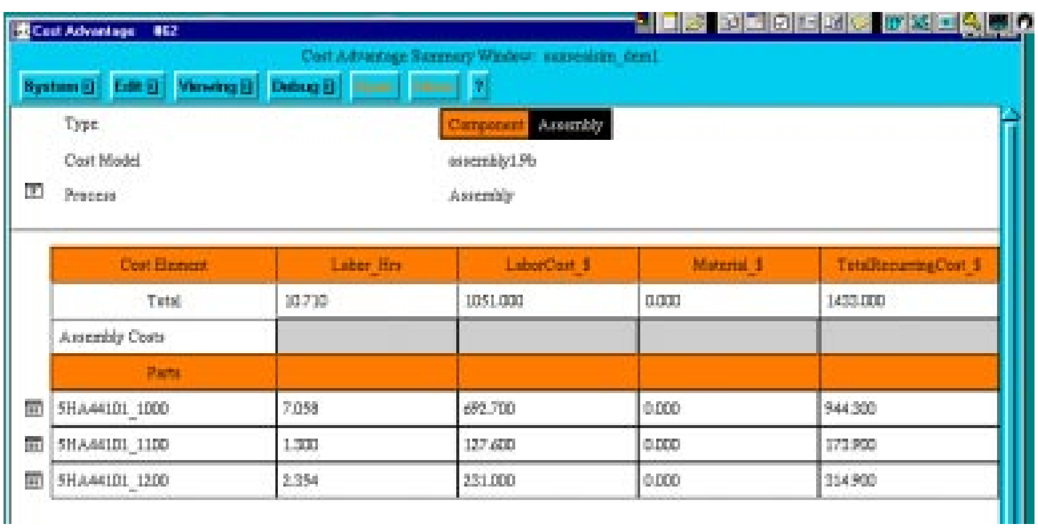


Cost Advantage Summary Window: 5HA44101_1000

Type	Component Assembly
Cost Model	assembly1.9b
Process	Assembly

Cost Element	Labor_Hrs	LaborCost_$	Material_$	TotalRecurringCost_$
Total	7.058	692.700	0.000	944.300
Assembly Costs				
SETUP01	0.351	34.480	0.000	47.000
VERIFY01	0.351	34.480	0.000	47.000
LOCATE01	0.422	41.380	0.000	56.410
LOCATE02	0.562	55.170	0.000	75.210
VERIFY02	0.351	34.480	0.000	47.000
SETUP02	0.351	34.480	0.000	47.000
LOCATE03	0.562	55.170	0.000	75.210
SETUP03	0.351	34.450	0.000	46.970
DRILL01	0.323	31.720	0.000	43.240
DRILL02	0.323	31.720	0.000	43.240
DRILL03	0.197	19.310	0.000	26.320
VERIFY03	0.738	72.410	0.000	98.710
DRILL04	0.492	48.280	0.000	65.810

Figure 6-15. Resultant CA Data for a Single Operation



Cost Advantage Summary Window: auxsealdm_deml

Type	Component Assembly
Cost Model	assembly1.9b
Process	Assembly

Cost Element	Labor_Hrs	LaborCost_$	Material_$	TotalRecurringCost_$
Total	10.710	1051.000	0.000	1433.000
Assembly Costs				
Parts				
5HA44101_1000	7.058	692.700	0.000	944.300
5HA44101_1100	1.300	127.600	0.000	173.900
5HA44101_1200	2.354	231.000	0.000	314.900

Figure 6-16. Cost Results for Auxiliary Seal Door Assembly

The **Query Manager** is a Java-based, web-enabled application developed by the SAVE team to allow members of the IPT to view and modify information in the SAVE shared database. The application allows traversal through the elements of the SAVE data model, as they are stored for a specific trade study or analysis. Figure 6-17 shows the elements of the initial load of the auxiliary seal door process plan, as it was written to the SAVE database.

Another helper application, which is not directly integrated into SAVE, is the **Electronic Design Notebook** (EDN). The EDN was used throughout the study to store pertinent simulation results and to document the decision process. Graphical information, such as the histograms from the tolerance analysis or the utilization charts from the factory simulation, was a prime candidate for storage in the EDN.

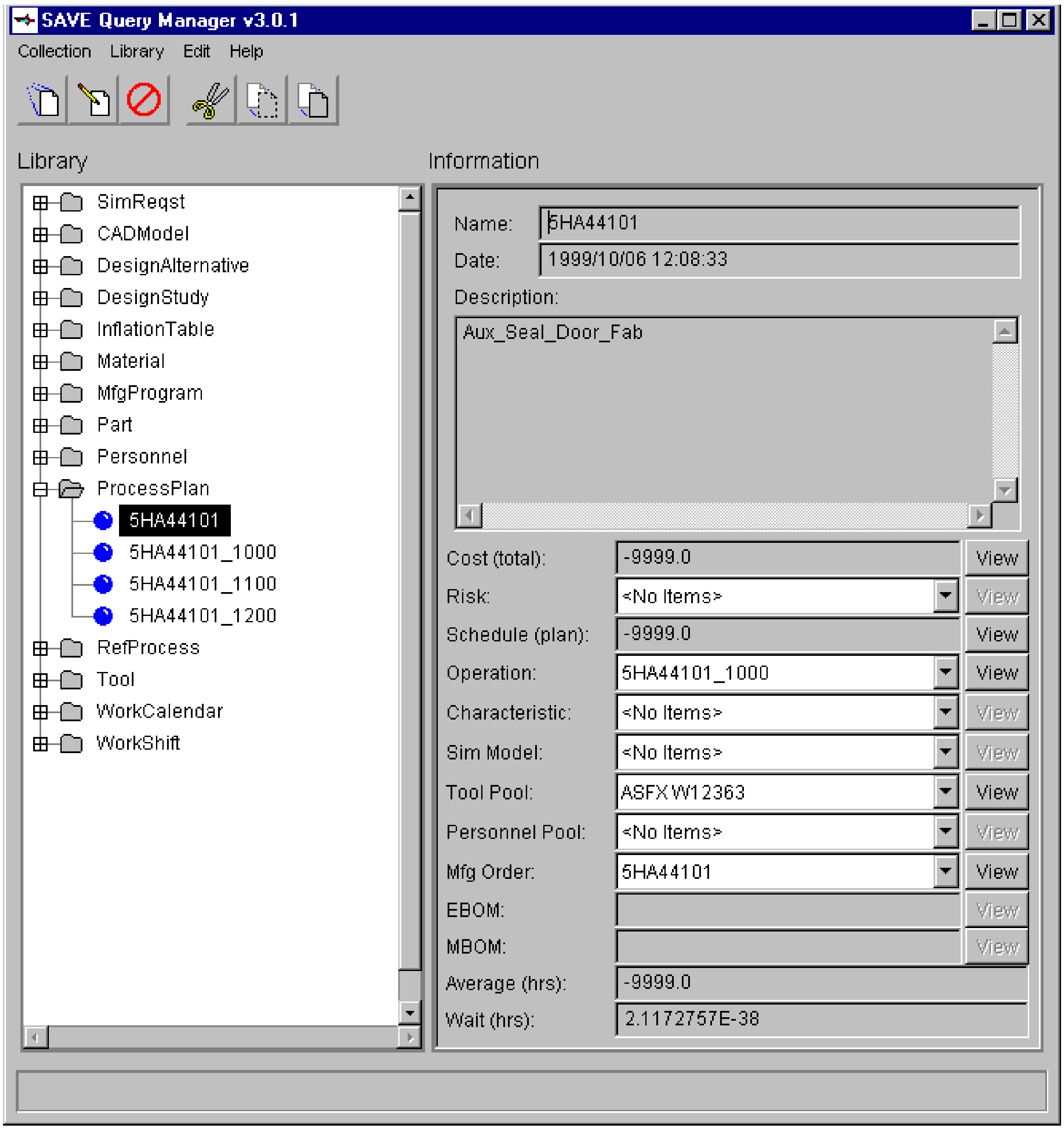


Figure 6-17. QM Shows Process Plans

4.2 Fit Check Trade Study

Figure 6-3, shown in Section 4.0 of this chapter, provides the overall flow for the fit check trade study. Basically, this study contains two parallel paths—one to evaluate the current process and another to evaluate the effects of adding the fit check. This section will only describe the path that includes the fit check; however, the conclusions will consider the results of both paths.

The ME on the team once again used **Microsoft Project** to develop the initial process plan for the fit check. The planning for the actual door installation was available, so the 17 operation fit check plan was based on that information. The Project plan including the operation sequence, associated parts and tools, and initial manpower estimates were exported to the SAVE environment and made available to the downstream simulation tools.

Symix Corporation's Factor AIM is a discrete event simulation tool that was used here to evaluate the effect of adding a fit check process on F-22 rate tooling. AIM imported the fit check operations, including labor and tooling requirements, from the SAVE environment. The simulation depicted in Figure 6-18, shows eight shared tooling resources with the midbodies moving through them as required. There are three processes taking place in the stations, two of which are existing processes while the third is the fit check. The simulation accounts for the full rate production tooling with phasing at the correct stage of the program.

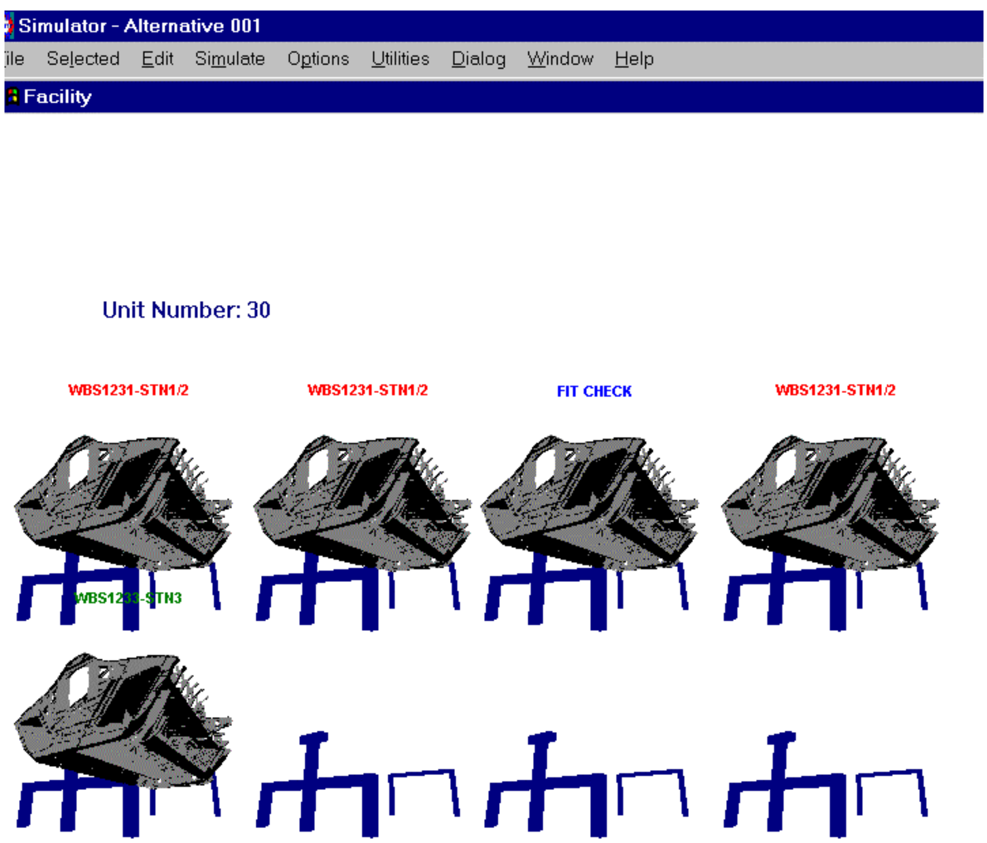


Figure 6-18. Fit Check Simulation

There were two key findings from this simulation. First, the addition of the fit check does not impact the rate-tooling requirement. Figure 6-19 compares the tool utilization both with and without the fit check. The graph indicates that seven tooling resources are sufficient to meet rate even if the fit check is added. Second, there was very little if any impact to the F-22 production schedule with the addition of the fit check. The simulation estimated approximately 9.5 hours to complete the process. An analysis of the number of "late" items indicates that, with the seven rate tools, the additional time required to complete the fit check did not significantly impact the on-time delivery of components.

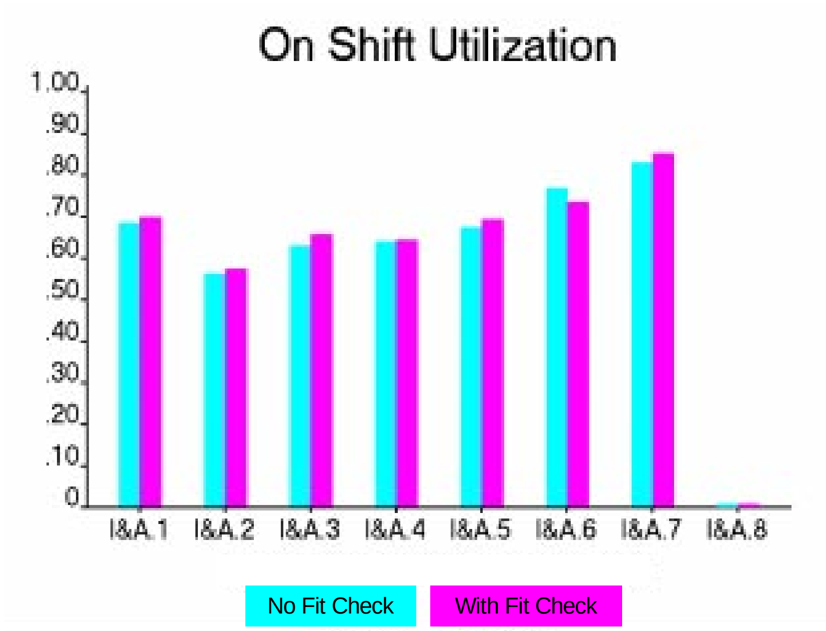


Figure 6-19. Tool Utilization Comparison

Factor AIM exported the resulting process times and tooling requirements into the SAVE database for use by other simulations.

Since schedule is one of the critical elements of the F-22 program, the SAVE team used **SAIC's ASURE** tool to evaluate the schedule risk for the fit check process. ASURE read the process plan including the operations and their associated schedule times. Ranges were assigned to the schedule data in order to perform the risk assessment. The results were displayed in graphic form, as shown in Figure 6-20. This particular graph illustrates the probability of success for a range of schedule values—for fit check times between 9.4 and 10.4, the schedule risk is minimal. These results were stored in the SAVE database.

Deneb's ERGO tool is a highly visual simulation tool used to assess the ergonomic issues associated with the fit check process. Similar to QUEST, ERGO imports the process plan, tools, personnel, parts, and their relative locations from SAVE and automatically generates the base simulation model. By automating the routine portions of the model generation, the modeling time is reduced by about 25%, allowing the analyst to concentrate on the more intellectually challenging modeling activities.

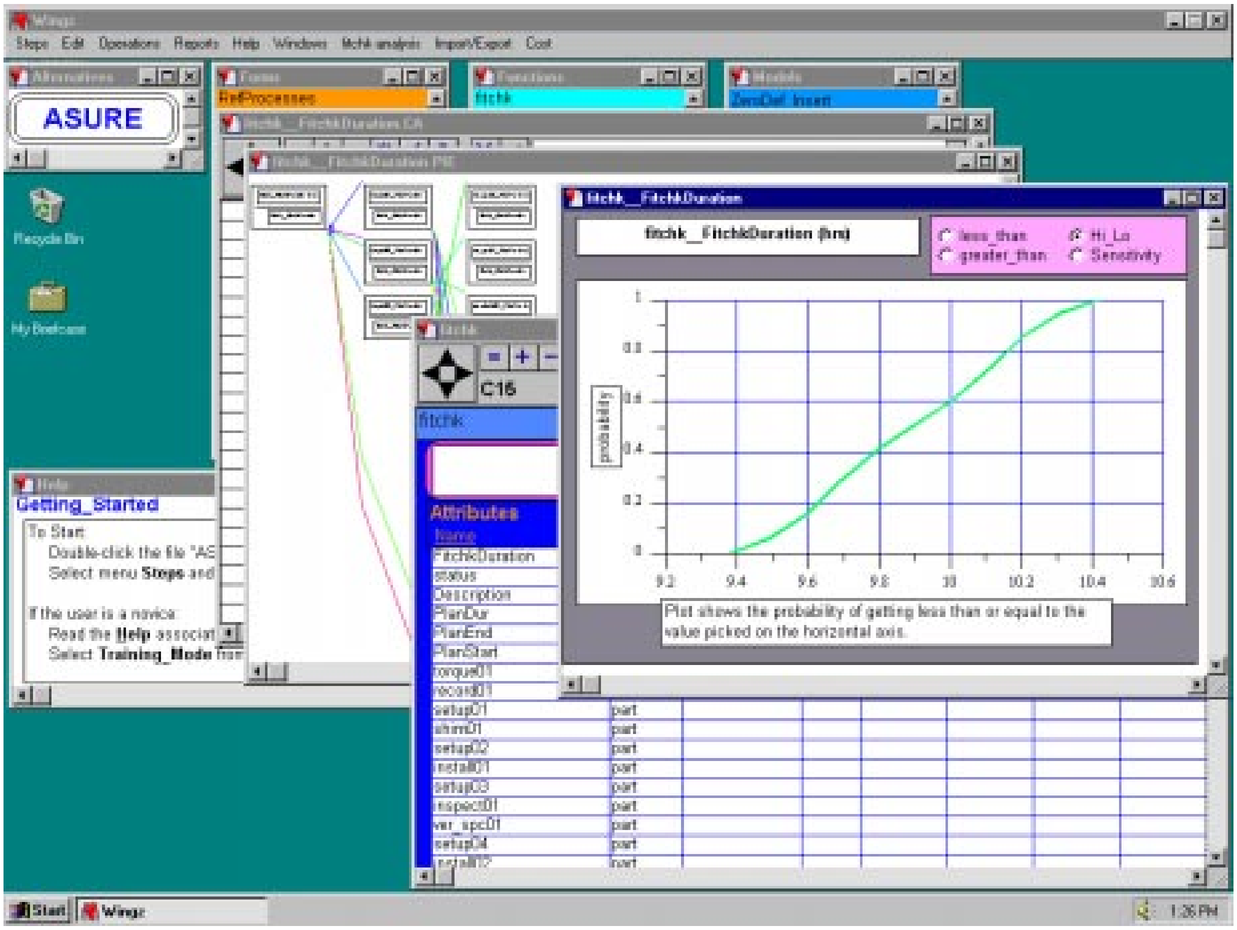


Figure 6-20. Schedule Risk Assessment

In this ergonomic analysis, a trade was performed to determine the number of personnel necessary to complete the door assembly fit check. The study included analysis for three, four, and five people. The results, depicted in Figure 6-21, indicated that there are five people required—four to hold the door in place and one to install the pins. Door weight and personnel positioning were deciding factors in the analysis.

The final assessment factor in the fit check study was a cost estimate. Once again, **Cognition Corporation's Cost Advantage** was used to make the assessment. In this case, CA used actual simulation results, imported from SAVE, for task durations and personnel requirements to estimate the cost. By using simulation results instead of historical data in the cost assessment, the resulting cost information was much more accurate. For example, in this particular analysis, there was a complex shimming operation in the process plan. Because the simulation modeled the actual work involved in performing the shimming operation, the time estimates were more realistic than the standard hours for shimming.

The cost analysis estimated the total recurring costs to be about $3000 for adding the fit check process. This cost, along with the schedule and risk impacts, were considered in the final evaluation of the fit check. Figure 6-22 shows the cost elements of the fit check that were exported to the SAVE database.

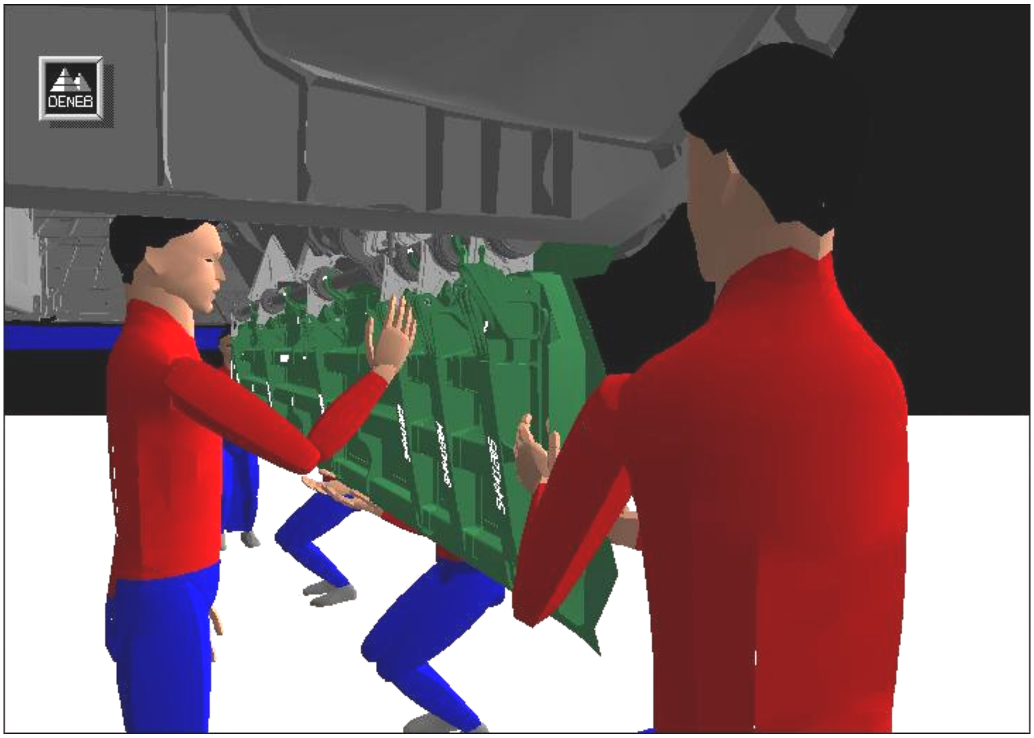


Figure 6-21. Ergonomic Analysis of Fit Check

Cost Element	Labor_Hrs	LaborCost_$	Material_$	TotalRecurringCost_$
Total	30.600	3003.000	0.000	3279.000
Assembly Costs				
torque01	1.000	98.140	0.000	107.100
record01	0.100	9.814	0.000	10.710
setup01	0.200	19.630	0.000	21.430
shim01	16.000	1570.000	0.000	1714.000
setup02	0.200	19.630	0.000	21.430
install01	1.000	98.140	0.000	107.100
setup03	0.600	58.890	0.000	64.290
inspect01	0.200	19.630	0.000	21.430
ver_spc01	1.000	98.140	0.000	107.100
setup04	0.200	19.630	0.000	21.430
install02	5.000	490.700	0.000	535.700
setup05	0.200	19.630	0.000	21.430
inspect02	0.200	19.630	0.000	21.430

Figure 6-22. Fit Check Cost Results

5.0 Metrics

Using the SAVE Virtual Manufacturing environment, the demonstration team concluded that the F-22 can achieve a successful, repeatable main weapons bay door installation by incorporating a change in tooling philosophy and adding a fit check process prior to midbody shipment.

In the OML versus IML Tooling Trade Study, the simulations showed that over 99% of the door mismatch and interference problems could be eliminated by incorporating the OML tooling concept and modifying the geometry on two tooling holes. This change alone reduced the installation time from about 36 hours to 16 hours. The F-22 Program incorporated the OML tooling philosophy on the shop floor during the same time that the SAVE analysis was being conducted. The preliminary results from the program are positive.

Although the F-22 program has not currently adopted the fit check, the feedback from the simulations provided some useful results that will be used in the program's decision process. The manufacturing simulations showed that adding the fit check could be accomplished with no additional tooling and with little or no impact on schedule. Although there is a slight cost associated with the fit check addition, the downstream cost savings will likely offset or possibly eliminate that cost. With the addition of the fit check, installation times should reduce to about 8 hours per door with a high probability of successful first-time installation.

Of the seven metrics initially identified by the SAVE program, the results of this demonstration summarized above showed an impact on the following five of these metrics:

- Design to cost data accuracy,
- Design change reduction,
- Scrap, rework, and repair reduction,
- Process capability, and
- Fabrication and assembly inspection reduction.

The impact of improvements in these metrics can be estimated using the SAVE Cost/Benefit Analysis discussed in the SAVE Software User's Manual.

The SAVE demonstration team was able to accomplish two studies of a complex problem area in a relatively short period of time by using the simulation tools within the integrated environment. Although the simulation tools themselves provide considerable benefits in assessing the impacts of design decisions prior to their implementation on the shop floor, the integration of these tools makes them more effective in their use. The SAVE environment facilitates extensive model and data reuse, thus reducing the simulation model generation times by 20-50 percent depending on the application. In addition, the synergistic effects of cost, schedule, and risk can be assessed with SAVE, where this capability is virtually impossible otherwise.

6.0 Defense Manufacturing Conference

The F-22 MWB door demonstration was presented at the Defense Manufacturing Conference (DMC) in Miami, FL during the week of November 29 through December 2, 1999. DMC provided the opportunity to present the SAVE concept and its potential to a wide audience of potential government and industry users.

7.0 Video

The SAVE team produced a ten-minute video that summarizes the goals and accomplishments of the SAVE program. This video provides highlights of the entire SAVE program from the initial proof-of-concept demonstration through the final verification and validation of the SAVE Virtual Manufacturing Environment.

Chapter 7

Technology Transfer

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 Introduction

The SAVE Technology Transfer plan consisted of several primary elements, each of which are discussed below:

- Outreach
- Coordination
- Advisory Boards – Operational Task Force and Technical/Business Advisory Board
- Beta Testing
- Commercialization Planning
- Implementation Planning – Cost/Benefits Estimation
- Planning for long-term ownership of SAVE Specification

Commercialization efforts originally considered two primary approaches: (1) vendors market their products with SAVE compliant capabilities and (2) the commercialization of infrastructure capabilities directly or through pay-per-use or Internet libraries. Early in Phase 2, the interest shown by the simulation tool vendors on the SAVE Team clearly indicated that the best path to commercialization was through existing software vendors. This approach has been pursued both for SAVE-compliant tools and for the elements of the infrastructure, as discussed below.

2.0 Outreach

A strong element of the SAVE Program's success has been the on-going effort to keep SAVE's vision, approach, and results visible to a wide range of potential users and software suppliers. A representative list of these outreach elements include:

- Presentations to DoD leadership including:
  - Rudy DeLeon
  - General Blot
  - RADM Trewby
  - RADM Steidle
  - General Hawley
  - Mr. Mark Schaeffer
- Presentations/Demonstrations at 1996, 1998, 1999 Defense Manufacturing Conferences
- Presentations at D. H. Brown Conference, 1998
- Presentations at ASME Manufacturing Week Conferences, 1997, 1999
- Presentation at American Welding Society Conference, 1999
- Presentation/Demonstration at Deneb Simulation Conference, 1998
- Presentation to Object Management Group Manufacturing Domain Task Force, 1999
- Presentation at SME Composites Manufacturing and Tooling Conference, 1999
- Presentation to Arnold Engineering Development Center, 1998
- AGARD Paper presented in 1998
- Articles in Aviation Week, May 13, 1996 and November 30, 1998
- Article in Manufacturing News, April 1996
- Article in CAE Magazine, November 1999
- Article in Manufacturing Engineering, May 1999
- Booth/Demonstration at ASME/SME Computer Technology Solutions, 1999

- Presentation at NASA Next Generation CAD/CAM Conference
- World Wide Web Site
- Information on JSF Website

3.0 Coordination

Coordination consisted of meetings with other federally funded initiatives, academia and JSF contractors. The results of the coordination activities include JMCATS integration into the Phase 1 SAVE system using interfaces developed by GRCI; two coordination meeting with Hughes on the integration of JMD into SAVE; discussions with SimTech, SMC, Raytheon MADE Program, LMMS Made Program; WL/FIB; NASA ADAM, NASA AMES, NIST, CTC, GIT/ECRC, SCRA/ECRC and the CSA program.

4.0 Advisory Boards

One of the primary goals of the SAVE program was to develop and implement an integrated virtual manufacturing environment that would provide affordability impacts to the JSF and be commercially viable for manufacturing simulation tools vendors. In order to insure that these goals were being met, SAVE established two advisory boards. The Operational Task Force (OTF) was comprised of members from the JSF contractor community. Their charter was to make recommendations relative to the objectives and approaches adopted by the SAVE team for implementing the VM environment on JSF. The Technical and Business Advisory Board (TBAB) included members from the vendor, government, and academic community. Their primary responsibility was to assess the recommendations from the OTF, along with the SAVE team's strategies to address those recommendations, relative to the reality of their implementation and use. Table 7-1 lists the members of the two advisory groups.

Table 7-1. OTF and TBAB Membership

OTF MEMBERS	TBAB MEMBERS
Lockheed Martin	JSF Joint Program Office
Boeing	Air Force Research Laboratories/MLMS
Northrop-Grumman	Cognition Corporation
General Electric	Deneb Robotics
Pratt and Whitney	Engineering Animation, Incorporated
	SAIC
	Symix
	Georgia Tech
	University of Southern California
	Massachusetts Institute of Technology

The original concept for the two groups included 6-month alternating intervals with meetings moving each time to provide a more equitable travel burden. As the program progressed, the format changed to a yearly joint meeting of the two groups. This format provided a more open exchange between the user and vendor communities and offered more immediate direction for the SAVE team. The findings from each of the joint meetings are summarized here.

4.1 OTF/TBAB Meeting on April 1, 1997

A joint meeting of the Operational Task Force (OTF) and the Technical/Business Advisory Board (T/BAB) was held on April 1, 1997. This was the first joint meeting of the two groups and everyone seemed pleased with this format.

Both groups voiced the opinion that early access to SAVE products by the user community was important to SAVE's eventual success. JSF contractors felt that early experience with SAVE was necessary to allow them time to fully assimilate SAVE and to maximize its impact on EMD proposals. The SAVE vendors expressed the opinion that SAVE might be overtaken by other events if it did not accelerate its products. These thoughts lead to a discussion of possible beta testing in the mid 1998 time frame. SAVE program management took an action item to consider program changes to allow such user testing and was successful in incorporating the beta tests into the program. The results of these beta tests are summarized in Section 5.0 of this Chapter.

Each member of the group was given time to discuss their view of SAVE and to raise issues for discussion. Eight items were identified for further moderated discussion. These are listed below with information about how the SAVE team has addressed the item.

How do we capture the lessons learned from SAVE?

This information is captured in the Implementation Plan, which is discussed in detail in the SAVE Software User's Manual and in Section 4.0 of this chapter. During the meeting, we discussed that fact that the cultural issues of implementation that we face in the SAVE contract efforts are similar, but not identical, to those faced by production software implementations. Beta testing started to address those issues, and we have attempted to document and share our lessons learned with the wider community.

The SAVE system was designed to be expandable, and the lessons we learned in developing the core will be useful to those who expand, continue to support, and implement the SAVE system. In particular, SAVE's use of the CORBA distributed object standard will provide lessons that are applicable to a wide range of systems development activities. We have made every effort to capture our experiences, include them in SAVE presentations, and summarize them in the final implementation report.

What will be the implementation/development cost of SAVE?

In response to this question and to actions from other advisory board meetings, the SAVE team developed a detailed implementation plan along with a cost/benefits or return on investment (ROI) spreadsheet. Both of these are of vital importance to the ultimate successful implementation of SAVE. This information is summarized in Sections 6.0 and 7.0 of this chapter and is discussed in more detail in the SAVE Software User's Manual.

Will SAVE results be able to have a maximum impact on EMD?

The timing of the SAVE contract dictates a focus on supporting JSF EMD. The SAVE concept and, in fact the core SAVE toolset (both categories and specific tools), could certainly be used in preliminary design. For example, there may need to be some adjustments in the level of detail of the cost model inputs, but these modifications are certainly possible.

SAVE took the first step toward accomplishing this by incorporating Beta Tests into the mainstream contract activities. This early use and testing of the system allowed the JSF community to get an early look at the possible impacts to the program.

The SAVE tool wrappers and infrastructure are now ready for commercialization. A number of commercial software vendors, both those who are team members on SAVE, and others who recognize the potential for SAVE integration, have expressed interest in producing SAVE-compliant tools and infrastructure. A list of these vendors is included in Section 8.0, Commercialization, below. These vendors are ready and willing to work with the JSF customers. With this timing, SAVE compliant tools (simulation tools, infrastructure, server, cost models) can be applied in relatively short order to the JSF, prior to EMD proposal submittal.

What is SAVE's detailed commercialization plan?

The importance of this issue was strongly highlighted at the OTF/TBAB meeting. The SAVE program has always recognized its importance, and worked during the last year of the program to bring it together. Inputs from the OTF members made it clear that a solid technical product and commitment to commercialization are both vital to SAVE acceptance by the contractor community.

The SAVE Team, including our commercial software vendors, met the day following the OTF/TBAB. We spent some time discussing the subject of commercialization. The results of this and additional planning throughout the rest of the contract resulted in the SAVE compliant software vendor list shown above in Table 7-1.

Can we have each contractor identify <4 desired capabilities for SAVE demos?

During the OTF meeting we polled each contractor for a list of the four SAVE tool categories they would like to see included in a beta test plan. The contractor votes covered essentially all SAVE tool categories; however, the contract limitations forced us to limit the Beta Test capability to a subset of the SAVE toolsuite. The SAVE demos, of course, utilized the full range of SAVE tools.

Can we have each contractor "buy-in" on data model requirements?

Throughout the program, the SAVE Team openly solicited any input on the SAVE data model. There was a wide distribution of the first and subsequent releases of the model to obtain the maximum feedback and acceptance. Review and basic acceptance by the vendor, government, and contractor communities provided one of the primary foundations for the success of the program.

How do we involve vendor associations to help SAVE commercialization?

Long term success of SAVE is dependent on wide spread acceptance and support for the SAVE specifications. We worked with our vendors throughout the program to identify appropriate vendor associations and made SAVE presentations as appropriate to gain their acceptance. The specific direction of the future ownership and support of the SAVE specification was discussed in detail at the last OTF/TBAB meeting summarized in Section 1.3.

How does SAVE work the other standardization activities?

For the majority of the program, the primary focus of the SAVE team was on understanding the data model requirements to support the manufacturing simulation domain. We concentrated on gaining acceptance from our own vendor and user community with the intent to explore related standards activities once we had a clear definition of our requirements. Early on, we identified other standardization activities (OMG, NIST, STEP, etc.) that overlap the SAVE domain. During the last 6 months of our contract, we worked with some of these organizations in an attempt to find the best fit for permanent ownership of the SAVE data model. The results of this activity are summarized in Section 6.0.

4.2 OTF/TBAB Meeting March 17, 1998

A joint meeting of the Operational Task Force (OTF) and the Technical/Business Advisory Board (T/BAB) was held on March 17, 1998. The primary topic for this meeting was to discuss and obtain guidance on issues of SAVE commercialization and organization for long-term ownership of the SAVE specification.

Mike Cronin, President of Cognition Corporation, presented his perspectives on the potential for the development of SAVE and application to problem domains beyond the current manufacturing simulation scope. Don Brown, of D.H.Brown and Associates, discussed the Open CAD Architecture Initiative (OCAI) and its possible role in SAVE development and extension to a wider range of CAx data integration capabilities. The OCAI might play a role in researching extensions, but does not currently look like the correct body to "own" the SAVE specification.

The standard OTF/TBAB format was followed, allowing each representative time to express views on SAVE and to raise issues. In general, interest remains very high, particularly as we approach the time when other organizations will be able to apply SAVE software to their own pilot projects.

4.3 OTF/TBAB Meeting June 22 and 23, 1999

A joint meeting of the Operational Task Force (OTF) and the Technical/Business Advisory Board (T/BAB) was held on June 22 and 23, 1999. The focus of this meeting was on developing a plan for the long-term ownership and support of SAVE in a commercial environment. The first day involved open discussion about the issues of commercialization with additional discussion on the impact of the Beta Test results. There was also an invited presentation from Larry Johnson, the chairman of the Manufacturing Domain Task Force (MfgDTF) within the Object Management Group (OMG). The second day's agenda focused on eight issues that surfaced on the first day as items of primary importance for the SAVE team in the quest for commercialization. A discussion of these issues, ranked by importance, is summarized below.

Ownership of the SAVE data model.

Two possible avenues were identified. The most popular with the SAVE vendors was to approach the Society of Manufacturing Engineers (SME) to discuss the possibility of forming a standards body within their organization to proliferate and maintain the SAVE standard. SME was contacted and has expressed interest in providing this structure.

The user community seemed more in favor of working with the OMG. The group decided to proceed with the OMG as a parallel path to the SME approach. As part of the OMG pursuit, the SAVE team submitted a response to an OMG Request for Information (RFI) in this area and presented the SAVE data model at the August, 1999 technical meeting of the OMG. There was a strong response from the OMG, and the group has expressed interest in proceeding with a Virtual Manufacturing Request for Proposal (RFP) for which the SAVE model is one candidate.

It will be up to the initial SAVE implementation sites and their vendors to decide whether to formalize a group under the SME or OMG.

More information about the ownership of the SAVE data model is available in Section 8.0.

Capabilities of the SAVE data model.

This issue primarily centered on the capability of the process plan object in the model with respect to handling multiple levels of detail. After discussing the issue with knowledgeable people within the planning community, the SAVE team felt that the model is sufficient to represent varying levels of detail and/or indenture. The model does not, however, contain roll-up and flow-down capability. Approaches to handle this are documented in the SAVE Software End Item document.

Business case for SAVE / ROI.

In order for SAVE to be successful, there must be a high return on investment. The advisory boards directed the SAVE team to develop a general template that could be used by possible implementers, including the JSF, to determine the benefits of deploying SAVE. This template is available and is discussed in further detail in Section 7.0.

Performance Issues.

System performance issues were identified in both the demonstrations and the Beta Tests. In order to address these issues, the SAVE team tapped several resources as listed below:

- Iona Technologies, Supplier of CORBA Compliant Orbix Software
- OMG Members with Implementation Experience
- Cognition Corporation, Developer of First SAVE Commercial Server

The results of these activities show that there are still significant opportunities to improve performance over the current levels by enhancing the server and wrapper code as well as by making modifications to the structure of the data model. The findings from these evaluations are documented in the SAVE Software End Item document.

Implementation Plan.

The SAVE team developed an implementation plan that includes IT, management and user views of the steps involved in implementing SAVE. This plan is detailed in the SAVE Software User's Manual document.

Wider commercial base.

In order to make SAVE commercially viable, there needs to be a wide enough commercial base to make selling the software profitable for the vendors while still affordable for the users. SAVE addressed this issue throughout the program by making SAVE presentations all over the country to a wide audience. Interest has surfaced within numerous organizations, including additional government players and members of the automotive industry.

Installation test data.

One finding from the Beta Tests was that there were not sufficient installation and testing instructions to verify a complete and successful SAVE installation. The requirement for this procedure was documented in the SAVE Computer Software End Item document.

Configuration management of SAVE data.

Configuration management capabilities, although available in the SAVE data model, were not very well understood by the Beta and demonstration teams. The SAVE approach here was to better document the available configuration management capabilities in both the SAVE Computer Software End Item and Software User's Manual documents.

Process planning tool.

The need for a process-planning tool within the SAVE toolsuite was identified as early as the Interim Demonstration. Although there were not sufficient funds to include that tool in the final demonstration, the need for it is well documented.

Naming services for connectivity/installation issues.

In order to improve system installation and connectivity, the SAVE team tested the use of CORBA naming services. A name service was developed for the SAVE server and tested with several representative clients, including the Query Manager. Initial results of these tests were positive with details available in the SAVE Software End Item document.

Certification of vendors.

When implementing standards, it is important to have a vendor certification process that verifies compliance with the standard. The responsibility for this certification will largely fall to the organization that has long-term support for the SAVE data model. Initial discussions with NIST indicate that they are interested in pursuing that role with the standards body.

Interaction with other domains.

The SAVE architecture and approach is viable for many other domains. Groups responsible for developing the models for those domains must be careful to identify any possible interactions and provide a mechanism for interoperability. One initial area of expansion, CAD features, was identified by Cognition Corporation. They have extended the part and feature area of the SAVE model to include additional information that they feel is useful and a commercially viable extension.

5.0 Beta Testing

The joint meeting of the SAVE Operational Task Force and Technical/Business Advisory Board held in early 1997, identified the need to accelerate the availability of the SAVE technical products (infrastructure and tool integration data model) and commercialization planning. The stated needs lead to a discussion of conducting JSF contractor beta testing during 1998. Following the OTF meeting, the SAVE team developed a plan for program changes to develop beta test software and support two beta test sites. This plan was approved by James Poindexter, SAVE Program Manager at Air Force Research Laboratory Materials and Manufacturing Directorate, and Lt. Col. Earl Wyatt at the JSF JPO. The plan was ultimately approved by the JSF Joint Program Office, and the SAVE contract was modified to include beta testing at the two JSF Prime Contractor sites, Lockheed Martin Tactical Aircraft Systems and Boeing Military Aircraft.

The primary goals of the beta tests are listed below:

- Provide early JSF end user exposure to SAVE potential.
- Address cultural issues of full scale SAVE implementation.
- Provide a forum for maturation of the SAVE concept and software.

5.1 Selection Criteria

Selection of the pilot test cases and the required SAVE capability were jointly determined by the test site personnel and the SAVE development team. The primary goal of the beta testing was to achieve a level of acceptance of SAVE by the contractor community that would allow them along with the SAVE commercial software vendors to commit to commercial versions of SAVE software prior to the end of the contract.

The following is a list of the criteria that was used in selecting the SAVE Beta Test teams and their test cases.

- Maximize Impact on JSF Affordability – A major motivation behind performing SAVE beta tests was to begin to build JSF contractor acceptance of the SAVE system and to start the implementation of SAVE on the JSF program. With this in mind, any beta activity that had a direct relationship to the JSF and JSF contractors was given a high priority.

- SAVE Tools Used in Test Case – The beta sites were required to identify test cases that utilized a subset of the simulation tools that were already in the SAVE tool suite:

- Symix, Factor/AIM
- Deneb, IGRIP/ERGO
- Deneb, Quest
- Cognition, Cost Advantage
- SAIC, ASURE
- EAI, VSA3D

In addition, the teams had to have current licenses for the tools, appropriate hardware for installation, and experienced users.

- Test Cases Must Be Open To the SAVE Team – The SAVE team had to be able to view test problem definitions, models, input data, and results to properly support the beta site and to maximize the positive impact on SAVE development.

- Test Cases Scoped For Three Months – SAVE resources and schedule dictated a three-month period of performance for the two beta tests. Testing was proceeded by a three-month preparation period.

- Identify and Measure Metrics – Tracking metrics for process improvements was an important element of validating the SAVE technologies. The SAVE team worked with the test sites to identify appropriate metrics and to define how data was to be gathered during beta testing to quantify the metrics.

- Test Case Documentation – Test sites had to be willing to document the test case scenario and results, including measured metrics. Preliminary plans called for briefing chart material suitable for presentation, first to the SAVE customer, and then, with approval, to a wide audience.

5.2 Preparation and Testing

The beta test activity spanned an 8-10 month period. The schedule was divided almost equally among preparation, testing and documentation. This section describes the tasks involved with the preparation and testing (6-8 months) portion of the beta test.

5.2.1 Test Case Selection

Both beta test sites selected JSF-related test cases. This was possible through agreements with the sites that no proprietary data would be released through the SAVE activities. Selection of JSF test cases was an advantageous decision because it greatly benefited the task of implementing SAVE on JSF in a timely manner.

5.2.1.1 Lockheed Martin Test Case

The Lockheed Martin test case focused on alternatives for the JSF vertical tail. The PWSC baseline was traded against the JAD alternative. The studies focused on analyses related to traditional and advanced manufacturing assembly processes and various material systems. Using SAVE, the beta team conducted multiple iterations to optimize component design, assembly process, tooling design, and resource requirements.

5.2.1.2 Boeing Test Case

The Boeing beta test case focused on the X-32 wing tip, shown in Figure 7-1. The design study provided a good basis for directing related activities for the PWSC. The X-32 wing tip was a good candidate for the following reasons:

- Small assembly, fastened and bonded
- Metallic and composite details
- Baseline data available (design, plans, etc.)

Using SAVE, the beta team conducted trades among three alternatives: superplastic formed, stiffened skin, and bonded composite.

Figure 7-1. X-32 Wing Tip

5.2.2 Tool Usage and Computing Environment

The beta sites worked together with SAVE team personnel to select a subset of the SAVE tools for use during the tests. The tool selection was dependent on several factors. Availability of and experience with the simulation tools at the beta site were primary criterion. After narrowing the field, the tools were evaluated based on their applicability to the trades being performed in the beta test case and the ability of the SAVE team to sufficiently develop the required integration to support the study.

The beta test sites provided their own commercial tools and hardware platforms while the SAVE team provided the SAVE unique software, including the tool wrappers. Table 7-2 lists the wrapped tools and platforms used for the beta test activities.

Table 7-2. Software and Hardware for SAVE Beta Test

Software	Hardware Platform, Operating System
SAVE Server	PC, Windows NT
SAVE Query Manager	PC, Windows NT
SAVE Work Flow Manager	PC, Windows NT
Cognition Cost Advantage	IBM RS6000, AIX
Deneb QUEST	Silicon Graphics, IRIX
Deneb IGRIP	Silicon Graphics, IRIX
EAI VSA3D	IBM RS6000, AIX
Dassault CATIA	IBM RS6000, AIX
SAVE Parser (Boeing Only)	PC, Windows NT
Microsoft Project (LMTAS Only)	PC, Windows NT

5.2.3 Installation and Training

Installation and training sessions were held at each beta site in January 1999. During these sessions, the core SAVE components were installed and tested with SAVE personnel providing guidance to the site internal system administrators. Since one of the criteria for simulation tool selection was the availability of personnel experienced in the use of the tool, the SAVE portion of the beta training focused on the new functionality provided by the tool wrappers. In addition, each team received classroom and hands-on training for the SAVE team-developed tools. These included the server, Query Manager, Work Flow Manager, and parser. As a part of the training session, the SAVE team provided detailed user's manuals for each component of SAVE.

Installation of the simulation tools and their SAVE-compliant wrappers were accomplished at a later date. This delay gave the site administrators time to configure hardware and to attempt to install the software. During visits to each beta site, the vendors were successful in fine-tuning their software and wrapper installations.

5.2.4 Wrapper Development

Both beta sites explored SAVE compliant wrapper development as part of their beta test activities. The developers at these sites were provided with the appropriate specification documents, the CORBA IDL, and sample client code. Boeing wrapped an internal cost-estimating tool with some success. Lockheed Martin wrapped Microsoft Project for use as their initial process-planning tool. Although the developers experienced some difficulty with the CORBA software support for Active-X, the wrapper was developed and used successfully both in the beta test and the final demonstration.

5.2.5 Testing Activities

Once all initial planning and preparation activities were complete, the beta sites began a 3-month period where the SAVE virtual manufacturing environment was used to evaluate the trade studies defined for the beta test. Some software problems were identified along the way, with the SAVE team responding quickly to needs for bug fixes or modifications.

5.3 Results

The beta test was quite a learning experience for both the JSF contractors and the SAVE team members. The overall message from the beta sites was that the SAVE concept has real potential. It is a sound foundation for data sharing with plug-and-play for multiple vendor tools and is a good application of the open architecture concept. There are, however, several high-level issues that need to be addressed before the system is ready for commercial implementation.

1. Existing components need “commercial” flavor. That is, they need improvements to provide a stable, user-friendly, and well-documented environment.

2. Some system expansion is necessary to provide a complete, usable system. For example, both the beta tests and the SAVE demonstrations identified the need to integrate a process-planning tool into the environment.

Since the beta test, the SAVE team has worked diligently with the tool vendors to understand how these issues would best be addressed. These results and recommendations are documented in detail in the SAVE Software End Item and Software User’s Guide documents. A top-level discussion of these items is included here.

5.3.1 Trade Study Results for Beta Teams

Both teams performed simulations to assess concepts related to their JSF designs. Since this information is highly proprietary, it is not included in this report. The beta teams did, however, brief the JSF program office on their findings.

5.3.2 Benefits of SAVE Integration

The beta teams identified several quantifiable benefits to the SAVE integrated environment. SAVE facilitates extensive data and model reuse, thus, reducing the time it takes to generate simulation models. In addition, this data sharing concept allows realization of synergistic benefits of integrated cost, schedule and risk assessments. Table 7-3 measured values for model generation times and the percent reduction in that time due to SAVE integration.

Table 7-3. Integration Benefits for Model Generation

Tool	Percent Savings	Generation Time
IGRIP	None*	10-40 hours
QUEST	50-75 %	10-20 hours
VSA3D	None*	60 hours
Cost Advantage	50%	2-3 hours

* SAVE automatic model generation capability was not available for these tools at the time of the beta test activities. Implementation and use on the SAVE final demonstration shows time savings similar to those experienced for the other tools.

5.3.3 Feedback and Recommended Improvements

The beta teams provided detailed feedback and recommendations in a number of areas of importance to SAVE. This feedback is summarized by category in the sections below.

5.3.3.1 Installation and Testing

System installation at the beta sites took much longer than expected. Most of the problems hinged around several factors: inadequate documentation (both in SAVE and commercial vendor products), inexperienced personnel completing the installation, incompatibility among software requirements for same machine, and irregularities in setup procedures.

The software product that caused the most problems was Orbix, the commercial CORBA software. The lack of definition of a client installation, the need to hard-code several variables (including IP addresses), and the sensitivity to other processes running on the machine were the primary areas of concern. The SAVE team has addressed these issues with Iona, the software vendor, and has made recommendations in the SAVE Software End Item document for dealing with these issues.

The ultimate goal for a commercially viable SAVE system would be to insulate the user and the system administrator from as many installation issues as possible. Ideally, the software components would be delivered with an installation script that any knowledgeable system administrator could run with ease.

5.3.3.2 Data Model Capability

The beta teams identified two overall areas of concern with respect to the SAVE data model. The first was related to the capability of the process plan object to model the level of detail required for use by different simulation tools. For example, a factory flow simulation may need a summary level process plan with all tools and parts for a given factory station whereas an assembly simulation may need detailed steps within one factory station that describe the assembly operations. Although the SAVE data model is quite flexible and provides a mechanism for modeling these levels of indenture, the user's had a difficult time understanding how to apply the capability. In addition, the teams identified the need for a rollup capability within the levels of the process plan in order to use it effectively.

The SAVE team addressed these issues in a detailed Concept of Operations document, included in the SAVE Software User's Manual. An understanding of the model, its capabilities, and the numerous ways to apply it are necessary for a successful application of the SAVE environment. This Concept of Operations provides information and guidelines for a successful application of SAVE.

5.3.3.3 Performance

System performance for the beta tests, at best, lacked consistency. The SAVE environment was highly sensitive to network traffic, as are many applications. There was also a disparity among the performance of different tool wrappers when interacting with the same data. Read and write times also varied both within and across wrappers. Table 7-4 provides some sample performance figures from the beta activities.

Table 7-4. SAVE System Performance Comparison

Tool	Data Accessed	Read/Write Time
IGRIP	Operation Cycle Time	1-3 Minute Write
QUEST	80-100 Operations	3-5 Minute Read
VSA	84 Operations	45 Second Read
VSA	4 Operations	10 Second Write
CA	80-100 Operations	2-3 Minute Read
CA	80-100 Operations	2-3 Hour Write
Project	80-100 Operations	3-7 Minute Read
Project	80-100 Operations	15-50 Minute Write

After reviewing the performance figures, the team documented some recommendations in the SAVE Software End Item document for making improvements in that area. One key finding is related to the way client access is implemented. The SAVE data model provides several mechanisms for data access, depending on the level and amount of data involved. Review of some vendor software indicated that more efficient methods could have been employed.

Early in the beta tests, some server performance problems were identified. These were caused primarily by memory leaks in the system. Most, if not all, of those problems were eliminated during the course of the beta tests.

5.3.3.4 Server/Back End

Although the SAVE architecture supports multiple back-end data stores, the beta test implementation included only a single repository. Both teams expressed the need to validate this back-end communication, specifically for relational databases and product data managers. For many companies, some components of the SAVE data model are already being stored and managed by these two types of systems. The SAVE Software End Item document contains written documentation about the process of connecting with these back-ends. The methodology, however, is quite dependent on the choice of commercial server implementation. The way the SAVE team would implement with the C++/Object Store server is different from the way Cognition would implement with their Knowledge Center approach.

The SAVE team did test a back-end connection from the “conventional server” to a relational database. As an example, some of the SAVE part attributes were built into a part table in a SQLServer database. The server was modified to “get” these attributes using ODBC connections when a client made a CORBA request for the part information. The connection was tested with the existing Query Manager application with total success. Some possible issues were identified with a full-scale implementation. These are documented in the SAVE Computer Software End Item document and are summarized in Chapter 2 of this document.

5.3.3.5 Documentation and Training

Both beta sites were provided on-site training and extensive written documentation for each of the SAVE-compliant tools. Even with these documents, the teams experienced problems with the installation and verification of the SAVE environment. These difficulties pointed to the need for a software test plan that includes step-by-step installation instructions for all SAVE components and turnkey examples that verify that the installation is correct. In addition, the beta sites expressed an interest in having a sample scenario that would familiarize the team with the use of the environment. This scenario would include a starting database, simulation models, an appropriate workflow, and documentation of the expected results.

The need for this additional documentation and training material is identified in the SAVE Software End Item document. It has also been communicated to potential SAVE commercial vendors.

5.3.3.6 General

One general comment was that there were too many things named "SAVE" in the beta environment—servers, directories, databases, files, etc. This caused some confusion for both system administrators and users. Future commercial SAVE environments will make careful use of the word. In fact, the future owners and sustainers of the model may rename the commercial versions of "SAVE" as appropriate.

5.3.3.7 Wrapper Development

Both beta sites worked to develop a SAVE-compliant wrapper for an internal application. The developers found the IDL straightforward and easy to understand. One site tracked wrapper development times for their programmer, experienced with C and C++ but not with CORBA. The entire development, including familiarization with the specification and the tool that was to be wrapped, took about 600 hours. Projections for an experienced CORBA developer who is familiar with the tool being wrapped estimate between 160 and 300 hours.

5.3.4 Summary

The beta tests were quite successful. The goals were accomplished, and the SAVE team obtained much useful feedback from the beta sites. As always, lessons are learned when conducting a software implementation and test of this magnitude and many mistakes (or learning experiences) would be avoided in future, similar activities. In hindsight, what would we have done differently to make the beta tests run more smoothly? These lessons can be summarized in five points that are listed below.

- Incorporate a process-planning tool prior to beta test.
- Allow additional time for software testing prior to release.
- Conduct software installation with vendor software representatives present.
- Provide a detailed test plan to the beta sites to verify software installation and connectivity.
- Provide more detailed user documentation and training.

6.0 Implementation Planning

In today's environment, a SAVE implementation should be considered a medium scale software implementation problem. The fact that SAVE involves several tools and an integration environment makes it more complex than implementing a single tool, but it is certainly less complex than fielding a Product Data Management (PDM) or Enterprise Resource Planning (ERP) system. Within the scope of medium scale systems, the complexity of implementing SAVE will vary from site to site, dependent on:

- The extent to which simulation tools are already in use.
- The level of current tool / organizational integration.
- The range of tools to be integrated.
- The size of the design organization which will use SAVE.
- The extent to which SAVE will be integrated into the larger design environment.

Rapid progress in the capability of manufacturing simulation tools has occurred in recent years, but many organizations have not fully embraced their use. One reason for this limited use is minimal integration among the tools, a problem that SAVE directly addresses. But a design organization must still grasp the concept and potential of simulation before the benefits of integration will be appreciated. Organizations that have applied isolated tools and have personal experience with the inefficiency of repeated data reentry will certainly understand the benefits of integration more readily.

One of the biggest challenges faced in deciding to implement system of SAVE-compliant tools is getting the multiple organizations usually involved in this range of tools to recognize that they can and should exchange their data in an iterative, real-time manner. In some large organizations, the tools currently integrated by SAVE are the responsibility of Design Engineering, Systems Engineering, Finance (Cost), Manufacturing Planning, and Tooling. Traditionally these organizations have developed systems that minimize their dependence on each other. Cost methods have been developed that are historically based and do not require timing estimates from planning or resource requirements from tool design. Factory scheduling does not utilize risk information that may be available for a particular unique design element. Design tolerance determinations are made in isolation of tool design and assembly process planning. Only through concurrent consideration of the interactions among all of these disciplines can a development team hope to identify better product and process designs and eliminate the costly errors currently found and resolved in production.

The concept of Concurrent Engineering has helped teams to recognize the significant benefits of information sharing, but the tools to support this concept have been slow to develop. The availability of an efficient means of information sharing can open all organization to sharing their data and willingly accepting data from other organizations to aid their own calculations.

In general, the benefits of SAVE integration will increase as the number of tools that are integrated increases. SAVE has currently been tested with six classes of tools, but there is a high degree of confidence that the current information-sharing model will support any class of tool within the manufacturing simulation problem domain. The benefits of SAVE integration will still be apparent with a small number of tools if they are from different, competing vendors and do not have any inherent integration. For example, the Deneb assembly and factory simulation tools, Envision and Quest, are well integrated and little would be gained from SAVE integration of them alone. However, if an organization wished to use Deneb's assembly simulation and Tecnomatix's factory simulation tools, then SAVE integration would have a high payoff, and be much simpler than custom integration.

The size of a design organization will have some impact on SAVE implementation planning. Larger organizations will certainly present some additional challenges such as how to organize the simulation teams or how many Data Model Servers to utilize. The flexibility of the SAVE architecture is a double-edged sword. It can fit to many different requirements, but it will require some consideration to determine the best option for a given implementation. Details of these options will be discussed below.

One of the major architectural features of SAVE is the ability for a simulation tool to access data from SAVE without regard to where the data are physically stored. This abstraction of data access allows data to be maintained in existing databases or PDMs without the data management issues created by replicating data in more than one system. In this way, it can be much easier to integrate SAVE into the larger design environment. An implementation site is not forced to use this feature. SAVE will store all data locally if desired, but in many implementations it will be desirable to have the SAVE server access its data from existing databases. This capability does not require reprogramming of the server, rather simply loading data to inform each data object or attribute about where the data are physically stored. Use of this capability implies an additional task in implementation, and this is more fully described in a section below.

The following sections of the implementation plan will be organized by the major phases in implementing SAVE.

Initial decision to implement
Pilot application
Planning for full-scale implementation
Implement full-scale system

Not all organizations will use all phases, but they are included for completeness. Within each phase there is a discussion of implementation from three perspectives:

- Management
- End users – these are the design team members who will operate the simulation tools
- Implementers – typically these are persons with IS experience

7.0 The Business Case for SAVE

Developing a solid business case for SAVE will be an important part of implementation planning at most sites. With so many technological advances occurring so rapidly, it is easy to become overwhelmed, making decisions on which technology and when to implement difficult. What may appear clear-cut to developers and some end users must still be sold to other end users and management.

A convincing business case needs to be tailored to each site considering SAVE implementation. As discussed in this section, the elements of both the cost and benefits are dependent on the specific status and capabilities of a development / production organization. Implementation costs will vary with the extent to which manufacturing simulation is already in use. Benefits will also be a function of how much simulation is in use and the historical design error rates, among other things.

7.1 Implementation Costs

Implementation costs are a function of many variables, and inputs are required from both end users and implementation personnel. A sample spreadsheet that can be used to estimate SAVE implementation cost is discussed in the SAVE Software User's Manual. Most inputs are easily available to an implementation site and are summarized below:

1. End User Inputs

    - Number of designers on design team
    - Number of manufacturing engineers (ME) on design team
    - Number of major parts in assembly
    - Number of major subassemblies
    - Manhour wrap rate
    - Number of legacy tools to wrap
    - Include a pilot exercise?

2. Implementers Inputs

    - Training manhours per tool
    - Number of backend data stores
    - Number of data objects remotely stored
    - Number of servers
    - Cost of server H/W platform
    - Installation manhours per simulation tool
    - Installation manhours per server
    - Average cost of PC for simulation tool
    - Average cost of UNIX platform for simulation tool

3. Costs obtained from S/W vendors

    - Server
    - Work Flow Manager
    - Query Manager
    - Cost Tool
    - Risk Tool
    - Assembly Simulation
    - Factory Simulation
    - Computerized Process Planner
    - Tolerance Analysis
    - Electronic Design Notebook, per user

4. Other Assumptions

   - Fraction of MEs performing simulations
   - Average size of simulation team
   - Estimated hours to wrap one legacy code
   - SAVE infrastructure training hours per user
   - Cost to implement remote storage for 1 object

This spreadsheet was developed to require a moderate number of inputs that can be easily gathered during the Initial Decision to Implement Phase to aid that decision. Reasonable estimates for all inputs are included with the spreadsheet. It should be considered a good starting point, but can be extended to more detail if desired. Section 6.0 shows the inputs and results for a sample estimate based on a medium size design team that involves approximately 100 designers, 60 Manufacturing Engineers and a product with 1000 parts in 4 major subassemblies. The Microsoft Excel spreadsheet can be obtained by contacting James Poindexter, Air Force SAVE Program Manager (james.poindexter@afrl.af.mil).

Note that the spreadsheet produces the costs broken into two categories:

- Cost of implementing simulation tools
- Cost of implementing SAVE-compliant integration

This was done to address a specific request of the SAVE Advisory Boards at the June 1999 meeting to separate the costs and benefits of the simulation tools themselves versus the SAVE integration. The benefits discussion and spreadsheet also address these categories to aid in the two-level implementation decision—simulation and/or integration.

7.2 Integrated Manufacturing Simulation Benefits

The other side of the business plan involves the benefits of SAVE. Their estimation is somewhat more problematic. The approach to this assessment follows the metrics that were identified early in the SAVE development effort. Each of these metrics is briefly described below. A SAVE benefits spreadsheet is available to aid an implementation site in developing a sound business case for SAVE.

7.2.1 SAVE Metrics

The following areas were identified as being the key metrics that would be improved by implementing a suite of integrated manufacturing simulation tools.

- Design Change Reduction – This metric measures the reduction in redesign which results from errors and inadequate consideration of producibility and manufacturing costs. An estimate of the benefits in this area are calculated by knowing the historical quantity of design changes per part per year and the average cost of a design change. In estimating the impact of manufacturing simulation it is important to account for the benefits derived from other technologies such as 3-D CAD and digital mockup. Measuring a reduction in design error relative to historical levels validates improvements in this metric.

- Design to Cost Accuracy – The objective of this metric is to produce consistent, accurate cost estimates of close, competing product and process alternatives. Ability to reliably choose between alternatives directly relates to cost estimation accuracy. Manufacturing simulation can have a strong impact on costing accuracy if time estimates, risk assessments, and resource requirements are included in cost estimating relationships, rather than simply using historical or weight-based methods. Comparing estimated cost to cost measured on the production floor is the way to validate improvements in this metric.

- Scrap, Rework, Repair Reduction – This metric is aimed at measuring a reduction in scrap, rework, and repair (SRR) which result from errors and inadequate consideration of producibility and manufacturing cost. The savings can be estimated knowing the historical parentage of SRR based on unit product cost and an estimate of the impact of integrated manufacturing simulation tools. Similar to the Design Change metric, it is important to account for the benefits derived from other technologies such as 3-D CAD and digital mockup. An organization that currently tracks SRR and categorized causes will find it easy to assess potential improvements from each of these design technologies. Measuring SRR after implementing SAVE will validate this metric.

- Design To Cost Accuracy – The objective of this metric is to produce consistent, accurate cost estimates of close, competing product and process alternatives. Ability to reliably choose between alternatives directly relates to cost estimation accuracy. Manufacturing simulation can have a strong impact on costing accuracy if time estimates, risk assessments, and resource requirements are included in cost estimating relationships rather than simply historical or weight-based methods. The integration of simulations and costing provided by SAVE makes detailed cost models practical. Comparing estimated cost to cost measured on the production floor is the way to validate improvements in this metric. This benefit is computed from estimates of the number and average value of design trade studies to be done, the number of units to be produced, and the difference in percentage of correct cost-based decisions provided by more accurate cost models.

- Fabrication & Assembly Inspection Reduction – This metric quantifies the benefits of reduced fabrication and assembly inspection that results from developing simpler, higher quality manufacturing tools and processes. This metric can be quantified by knowing the historical cost for inspection as a percentage of production cost and applying an improvement factor estimated for SAVE. The factor currently used was estimated by members of the F-22 Advanced Tactical Fighter Integrated Product Development Teams. Tracking future inspection requirements against historical levels is used to validate improvements in this metric.

- Inventory Turn Increase – This metric addresses the savings that can be achieved by reducing inventory cost by eliminating non-value-added activities and reducing fabrication and assembly process times. Measuring this metric involves estimating the financial cost of carrying the portion of inventory that is not actively being processed. Many companies currently track this metric, and validation of improvements due to improved manufacturing processing can be clearly measured.

In the development of these metrics, the SAVE system and its capabilities were described to members of the F-22 Advanced Tactical Fighter program design Integrated Product Teams and they (not the SAVE developers) estimated the factors used in the equations used to estimate improvements in the metrics.

8.0 Commercialization

The importance of SAVE commercialization was recognized as an integral part of the contract effort. Commercialization of the software elements of SAVE was correctly viewed as the key to full buy-in by potential users and to solid long-term support for the concept. This was clearly voiced by several of the Operation Task Force members at the OTF/TBAB meeting in early 1997. They stated that for SAVE to be ready for implementation on JSF users wanted early hands-on experience with SAVE (beta tests) and a clear understanding of the SAVE Team's approach to commercialization. Implementation and commercialization were recognized as a "chicken and egg" situation. Users want commitment to commercial products before they decide to implement and vendors want user commitment to implement before they produce commercial products. The SAVE Team has worked both sides of this issue to achieve the desired success.

Early in the SAVE program, consideration was given to a new, start-up company to produce and sell SAVE infrastructure elements (Data Model Server, Workflow Manager, Query Manager, Design Notebook). Strong support for SAVE from the software vendors on the team soon showed that the best approach was to simply provide them, and potentially other interested vendors, with rights to produce and market the SAVE system. This remains our approach today.

Several vendors who are not team members heard about SAVE, requested information and meetings, and expressed interest in developing SAVE-compliant tools or infrastructure elements. The combined list of supportive vendors is shown in Figure 7-2.

Several pieces of software developed by SAVE are commercially available today. These include:

- SAVE Data Model Server – Cognition Corporation

- CATIA to Cost Advantage CostLink – Cognition Corporation

- Cost Advantage Cost Models (Sheet Metal, Composites, Machine Parts, Assembly) – Cognition Corporation

As a final step toward maturing the SAVE software developed under this contract, several of the simulation tools were tested in conjunction with the Cognition Corporation Data Model Server, which is developed on the Knowledge Center ™ object management system. This commercial-quality server had been developed, but not used in the SAVE contract demonstrations.

The SAVE-compliant wrapped simulation tools used in the contract effort can be commercialized rapidly, as users request these tools.

- Deneb IGRIP/ERGO
- Deneb QUEST

- Symix FactorAim
- Engineering Animation Inc VSA-3D
- SAIC ASURE

Vendor	Contact	SAVE Tools	SAVE Infra-structure	Operational Software
Deneb	**Bob Brown 248-267-9696**	✓	✓	✓
Cognition Corporation	**Michael Cronin 781-271-9300 x222**	✓	✓	✓
Science Applications International Corp	**Jalal Mapar 703-748-5085**	✓		✓
Engineering Animation Inc	**Cliff Bliss 248-455-0133**	✓		✓
Tecnomatix	**Greg Almond 972-687-9032 Dave Chambliss 972-687-9030**	✓	✓	
Parametric Technology Corporaton (WindChill)	**Mike Brown 770-751-6607 x233**		✓	

Figure 7-2. Commercial Sources for SAVE-Compliant Software

The SAVE Workflow Manager and Data Model Query System are both nearly fully functional, and could be commercialized with little delay.

With the vendor side of commercialization shaping up well, attention has been focused on commitments from potential users and a plan for long-term ownership, support, and growth of the SAVE specification. Planning for ownership of SAVE following the contract is discussed in Section 9.0 Interest from Lockheed Martin, Boeing, and possibly a non-aerospace user should provide the “critical mass” for early commercialization. For this reason, we are expending a small effort in the commercial manufacturing arena to promote SAVE use.

9.0 Long-term Ownership of SAVE Specification

A cornerstone of the SAVE concept is that the integration approach must be an open, industry accepted specification for data sharing among manufacturing simulation tools. This specification must be accepted by groups of users and vendors, some of which strongly compete in their markets. One or two companies cannot control the specification if users expect to find a wide range of SAVE-compliant tools on the market. Only with an open specification will vendors find SAVE to be commercially viable, and users benefit from tools that can be integrated “out of the box”.

While a solid plan for commercialization is important, the need for an approach to shared ownership of the SAVE specification cannot be overlooked. The topic of long-term support for a growing SAVE specification was the topic at two OTF/TBAB meetings. At the meeting on June 22, 1999 two approaches were presented and discussed. The first approach was to form a new SAVE Coalition of user and vendor companies to manage and extend SAVE. The charter for the coalition was similar to one that is being pursued by a Meta Data Coalition found on the World

Wide Web. Ideas for the management structure, technical workings, and fee structure were presented. The second approach was to form an integrated manufacturing working group within the Manufacturing Domain Task Force of the Object Management Group (OMG). Larry Johnson, who chairs the Manufacturing Domain Task Force, presented this approach, and expressed strong interest in having SAVE become part of the OMG activities.

During the ensuing discussions a third approach was identified, that of forming a SAVE group within an existing related industry group, specifically the Society of Manufacturing Engineers (SME). The major motivation for this approach was to allow the SAVE group to develop an efficient, rapid process for establishing a SAVE standard and getting it to market and productive use. Existing standards bodies such as the OMG can take two years to achieve a commercial standard. Larry Johnson understood the direction given to the SAVE Team, but asked that SAVE still respond to the OMG Manufacturing Domain Task Force's RFI for potential standards in this area. The SAVE Team's response to the RFI is included in an appendix in the SAVE Software User's Manual. The SAVE Team gave a presentation of its response at an OMG meeting in San Jose in September and a number of OMG members expressed strong interest in incorporating SAVE into an upcoming RFP.

The SME was contacted and initial indications showed good interest on their part. Jim Slaughter of SME is contacting a range of SME participants to gage their interest and internal issues of whether SME should enter into the standardization process are being discussed. A final determination is expected from the SME in the next few months.

As discussed above, there are two viable approaches for continued support and development of SAVE. The final choice will be determined by the first few users who commit to SAVE implementation, and the vendors they select for providing fully commercialized SAVE-compliant tools.

Chapter 8

Program Summary

SAVE Final Report

Contract Number F33615-95-C-5538

CDRL A001

1.0 Results

The following objectives were identified for the SAVE Program over five years ago:

1. Develop a concept of operations for an integrated set of manufacturing simulation tools to achieve more affordable JSF development and production.

2. Develop an infrastructure to integrate commercial simulation tools to support that concept of operations.

3. Demonstrate the SAVE solution to inform potential users, test the technical approach and to validate projected savings.

4. Establish a strong technology transfer program.

5. Develop detailed implementation planning information.

6. Develop a viable approach to commercialization and continued support and growth of the SAVE concept.

7. Produce detailed system documentation to support both commercialization vendors and end users.

8. Promote the use of integrated manufacturing simulation tools on the JSF Program.

The CORBA-based SAVE Data Model approach to integration has been well accepted by both commercial software vendors and potential users. The SAVE Software User’s Manual presents both the SAVE Concept of Operations and detailed implementation planning information. A detailed Cost/Benefits spreadsheet was developed to help potential implementation sites develop their own business case for SAVE implementation and is included in the User's Manual. The three demonstration and beta testing, along with presentations and discussions with many organizations have made SAVE widely recognized throughout industry. Full validation of projected SAVE benefits based on demonstration results must await implementation of results in actual production. However, initial indications are that the percentage savings estimated for the key metrics are achievable from a well implemented, integrated system of manufacturing simulation tools. SAVE’s approach to commercialization is both simple and supported by existing software vendors, with some commercial tools based on SAVE developments already on the market. While no site has fully committed to SAVE implementation to date, several sites (both military and commercial industries) are seriously considering pilots or full implementations.

The SAVE Team believes that it has fully achieved the vision set out five years ago.

2.0 Conclusions

The following conclusions can be made based on SAVE program experience:

1. Today's virtual manufacturing simulation tools can accurately model a real manufacturing process cost, schedule, and risk. The SAVE demonstrations and beta tests have begun the process of validating that the significant affordability impact projected for VM are within reach.

2. It is possible to use an IPPT process that leverages simulation tools to reduce the cost of manufacturing fighter airplanes, even late in the production phase of a program. The supporting evidence for this conclusion is the $113,862 savings projected over the next production lot of aircraft on the F-16 program. Significant savings were also shown possible for the F-22 weapons bay door installation. The implication is that the sooner SAVE is implemented the greater the benefits will be. Also, it is feasible to implement SAVE in key areas of manufacturing late in production and still see a significant reduction in cost. This was also demonstrated in the Fast Track Demonstration Program.

3. The integration of simulation tools that enables data to be shared by the IPPT is key to keeping differing simulation, analysis and modeling tools synchronized (e.g., the process plan). The evidence of this was that during the model development for Phase I, process plans were modified to accommodate changes in the cost model; however these changes were not reflected in the schedule or risk simulation. It was a manual, sometimes painful process to keep these tools in sync. The implication of this is that for large scale programs with multiple IPPT's and large complex simulations, the integration and synchronization of these tools requires the use of a controlling infrastructure that includes a PDM. The SAVE architecture provides for management of key data in or through a PDM.

4. The approach used on SAVE demonstrated the ease of tool integration and the cost effectiveness of the integration approach. This was demonstrated by using existing commercially available interfaces for one commercial product; developing interfaces for six commercial products; and by an initial integration of JMCATS by the GRCI development staff. The implication of this is that for a very small investment (approximately $40,000) almost any tool can be rapidly integrated into the SAVE infrastructure.

5. The integrating infrastructure, in particular the data model, has been built flexibly so as not to constrain the design IPPT. SAVE does not attempt to rigidly define or codify a rigid process for using the set of simulation tools. Rather, the IPPT, through the work flow manager and data model will control the order in which tools are run and the data that each use and output to the data model. This places some additional burden on the IPPT to understand the data flow among tools, but the more rigid approach would severely limit the usefulness of the SAVE system.

6. The integration of virtual manufacturing tools is driven by a data structure that crosses product structure with process plan structures. This approach is clearly seen in the SAVE Data Model. The implication is that a standard representation method for processes needs to evolve so that this representation can be easily implemented throughout industry or that industry can read and write to the representation.

7. Commercialization of SAVE now hinges on end-user interest in the system. Frequent presentations and publications supported by openly available technical data have made SAVE widely recognized. Several sites are in various stages of considering pilot or full implementations. Commercial vendors are ready to support users with full commercial products.

8. A viable organization must be found to “own” the SAVE specification once the contract is complete. The SAVE team is aggressively pursuing this goal. Strong interest exists within the Object Management Group and the SAVE Team is working with the Society of Manufacturing Engineers to assess the viability of forming a SAVE Specification Group within that organization. Ultimately, the first committed users will make the final decision on the direction to take. At the completion of the SAVE program in September 2000, several sites were considering SAVE pilots or implementations, but no site had fully committed to an implementation.

3.0 Recommendations

The following recommendations are made based on experience with SAVE to date:

1. Apply the SAVE capabilities and IPPT concept of operations as soon as possible in a program; but, implementation even into the production phase of a program will still produce benefits.

2. When determining what to simulate, care must be taken to ensure that the anticipated return warrants the investment in the simulation model (in other words simulating every step in a process is not practical or affordable; therefore, simulate only those processes that are very complex or are not well understood).

3. Build models incrementally with as mature data as is available at the time the simulation is put together. The key to making simulation an integral part of the process is that it must be used through out the process.

4. A common definition of features that are the cost drivers of detail parts needs to be established to enable the rapid insertion of these technologies into industry. During Phase I an initial set of features for machined and hand laid up composites were developed. During Phase II this was expanded for sheet metal and assemblies. Additional studies to develop a comprehensive list and representation method should be pursued.

5. Users considering a SAVE implementation should already be familiar with manufacturing simulation tools and their benefits. It has been found to be difficult to sell integration to organizations that have not bought into simulation.

6. SAVE-supported tools involve a wide range of organizations in most large-scale companies. All involved disciplines including Systems Engineering, Design Engineering, Manufacturing Engineering, and Value Engineering should be engaged from day one in any process to assess and implement a SAVE system. All organizations

must recognize the advantages of sharing data in new ways to maximize the benefits of integration.